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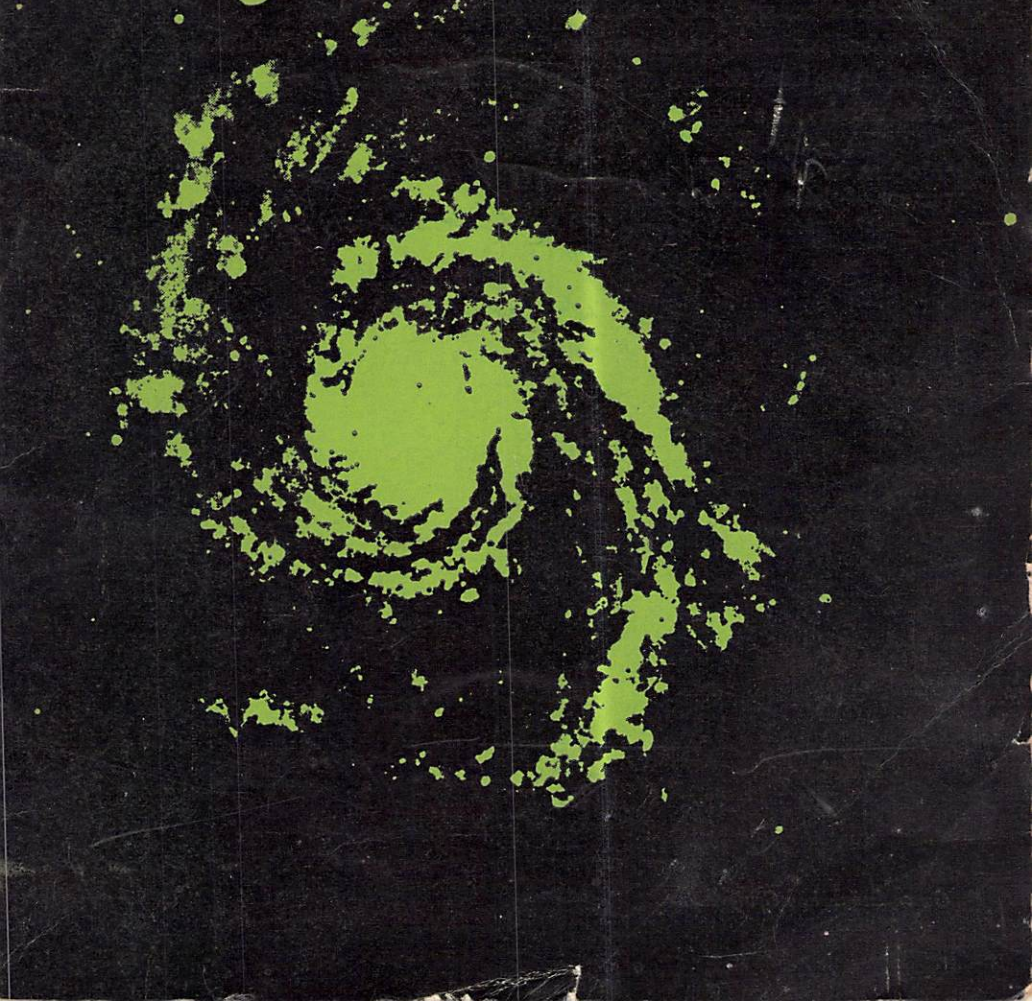
Peter M Millman

This Universe of Space



THIS UNIVERSE OF SPACE

by

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P.M.M., Ottawa

MEN AND TELESCOPES

1

To place our present knowledge of the universe in the proper perspective, it is necessary to go back to the very beginning of man's quest for a pattern in the world around him. Our remote ancestors, living in their caves, must have noted the regular recurrence of day and night and the waxing and waning of the moon. It is probable that these phenomena, together with the motions of the stars across the night sky and the recurrence of the seasons, first gave man the idea of order and regularity in his environment. It is interesting to speculate on what might have happened had the earth been surrounded by an impenetrable bank of cloud, which bathed the world in a monotonous half-light and cut off all chances of looking out into space.

But fortunately, we always have been able to look out into the star-studded sky, and, as a result, the heavenly bodies have been woven inextricably into the pattern of our normal existence. The sun regulates our daily activities, and we plant our crops according to the cycle of the seasons.

Since the dawn of human intelligence the sun and the moon have been recognized as moving across the background of fixed stars. To this pair of major luminaries, early man eventually added five more 'wandering stars': Mercury, Venus, Mars, Jupiter, and Saturn. With the recognition of seven bright and unique objects in the sky, the number seven became basic in our heritage of civilization. Of the seven days of the week, the names of three—Sunday, Monday, and Saturday—still clearly indicate their origin in the heavens.

In the fifth century before our Christian era Greek thought concluded that the earth was a sphere. By 250 B.C. Eratosthenes had obtained a figure for the size of the earth, accurate to within one per cent of the true value. But results such as these proved to be far ahead of their day and were often forgotten. The ancient observers of the heavens were actuated by various impulses; but, more than any other, it was the desire to interpret the will of the gods or an attempt to forecast the future which encouraged the gathering of astronomical knowledge.

We find cosmologies—that is, theories about the universe—which involve a flat earth, possibly supported on the back of a giant turtle or some other creature, and surrounded by water or mountains. The stars were hung from the arched vault of heaven, and across this vault the sun was driven in a chariot or conveyed in a boat. This vehicle was supposed to enter a subterranean tunnel at night. Experimental scientists were few and far between, and the problems of natural science were generally studied by pure thought, strongly coloured by religious belief. For example, the circle was considered the perfect figure, and for centuries every attempt to explain the motions of the planets involved only circles and systems of circles. There were some early theories where the earth was considered to move; but mostly it was thought of as the fixed centre of the universe, and it was heresy to believe otherwise.

Significant advances in our knowledge generally resulted from a step-by-step process, a human chain-reaction if you like, in which each scientist made use of the work of his predecessors and then passed on his own contribution to the next generation. Let me sketch for you an outstanding chain-reaction in astronomy.

In A.D.1560, just two years after Elizabeth I had ascended the throne of England, a young Danish nobleman in his early teens observed an eclipse of the sun. This event strengthened his already growing interest in astronomy, and, much against his family's wishes, he pursued his studies of the heavens at a number of universities in Europe. During this period, the young Tycho Brahe gained quite a reputation as an expert observer of the stars. But he lived the typical life of a student as well and managed to lose his nose in a duel of honour. For the rest of his

life he wore an artificial nose of gold—a fact that was verified recently by the exhumation of his body in Prague.

Tycho soon found that the current tables for predicting planetary positions were woefully inaccurate and he was fired with the urge to discover what was wrong. Tycho was undoubtedly one of the greatest natural observers the world has seen and fortunately his talents were not to be wasted. When the young astronomer was thirty years old King Frederick II of Denmark became interested in him and gave him an island off the coast, just north of Copenhagen. Here, backed by royal patronage, Tycho Brahe built Uraniborg, the first great astronomical observatory in the modern sense of the word. Here he played host to visitors from all over Europe, students and university professors, kings and princes, in a style more lavish than that displayed by any astronomer before or since.

The instruments which Tycho built for use at his establishment far exceeded in quality any previously used—celestial globes, armillary circles, sextants of various sizes, and a great quadrant of wood and brass nearly seven feet high. With these he was able to determine the positions of stars and planets to within one or two minutes of arc, or about one-fiftieth of a degree—more than ten times the accuracy with which other observers had been content. And remember, this was accomplished by naked-eye observation, for Tycho died before the telescope was invented.

Tycho was the first astronomer to recognize the value of a long and continuous series of good observations. For twenty years, surrounded by a group of students and assistants at his island observatory, he compiled a new star catalogue of over 750 accurate star positions and extensive tables of the positions of the moon and planets. Unfortunately, when Frederick II died, Tycho lost his royal support and was forced to leave Uraniborg. He spent the last few years of his life at Prague, as astronomer to the Emperor of Germany, and there he was joined by a young German assistant, Johannes Kepler. Kepler came from a poor family and had a weak physical constitution, but he was endowed with tremendous perseverance and a passionate desire to find geometrical harmony in the universe.

Tycho Brahe bequeathed to Kepler his long series of observa-

tions. Then followed years of labour during which Kepler, with infinite patience, made trial after trial, attempting to fit Tycho's observations of Mars into some system of circles piled upon circles. At last Kepler came to realize, much against his own inner conviction, that no system of circles, however complicated, was going to solve the problem. The best circular orbit left Mars in error by eight minutes of arc. Tycho could never have made a mistake of this magnitude.

Finally, the true nature of the orbit of Mars as an ellipse became so obvious to Kepler that he was forced to renounce the classical concept of circular motion once and for all. This concept had become firmly entrenched in scientific thought over many centuries. It is hard for us now to realize what a radical step Kepler took in proposing that all planets moved about the sun in ellipses, with the sun at one focus. This was the first of Kepler's three laws of planetary motion *(Fig. 1)*. And coincident with this first law, Kepler arrived inevitably at the second: that a straight line drawn from planet to sun sweeps over equal areas in equal times; in other words, the closer a planet is to the sun, the faster it moves *(Fig. 2)*. These laws reduced to one simple logical system all the planetary motions, which in the past had been a confused maze of small inconsistencies. And these laws have stood the test of time, for they still define the basic motion of all masses in our visible universe, from the latest artificial satellite launched in orbit round the earth to the most distant pair of galaxies located at the limits of observation.

Kepler's third law of planetary motion, which he deduced after a further ten years of studying the harmony of the celestial bodies, related the orbits of the various planets to each other *(Fig. 3)*. It gave a simple mathematical relation between the period of revolution of each planet about the sun and its distance from the sun. This indicated that the motions of all the planets operated according to one law of force. Kepler himself talked about a force associated with the sun and realized that it must diminish with distance. But he did not know enough about the mechanics of motion to carry the argument further. And so he missed the grand final step, which a young professor at Cambridge was to formulate nearly fifty years later.

Isaac Newton was the perfect example of an absent-minded

FIG. 1. *Kepler's Laws —I.* All planets move in ellipses with the sun at one focus. If an ellipse has foci at F_1 and F_2, and P is any point on the ellipse, then $PF_1 + PF_2 = \text{constant} = 2a$, and the eccentricity is defined as

$$e = \frac{c}{a} = \sqrt{1 - \frac{b^2}{a^2}}$$

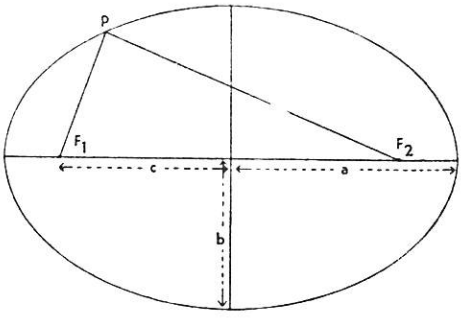


FIG. 2. *Kepler's Laws —II.* A planet, P, moving about the sun, S, at one focus of the ellipse, will take equal times to move P_1 to P_2, P_3 to P_4, and P_5 to P_6, when area P_1P_2S = area P_3P_4S = area P_5P_6S.

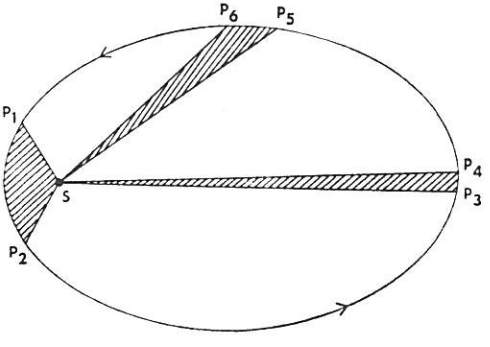
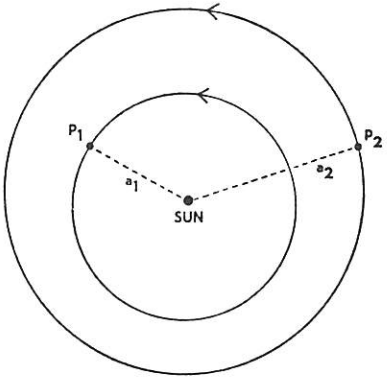


FIG. 3. *Kepler's Laws —III.* If planets P_1, P_2, at mean distances from the sun of a_1, a_2, make one complete circuit in the respective times T_1, T_2, then:—

$$\frac{T_1^2}{a_1^3} = \frac{T_2^2}{a_2^3} = \text{constant}$$

(Note that an ellipse of low eccentricity closely resembles a circle.)



professor. So great was his ability to concentrate on the current problem engaging his attention that mundane occupations, like eating or getting dressed, were often forgotten. Newton had the advantage over Kepler of being familiar with Galileo's concept of inertia—the resistance of all matter to any change in its state of rest or uniform motion in a straight line. Newton realized that the elliptical orbits of the planets, as outlined in Kepler's three laws, gave evidence of a force centred in the sun that decreased with distance from the sun in a way that could be mathematically defined. A similar force centred in the earth must keep the moon in its elliptical orbit. In the year 1666, while fire raged in London and the plague ravaged England, the Cambridge University students had been sent home to avoid infection. Newton, just twenty-four years old, was thinking things out in the little town of Woolsthorpe, his boyhood home near Nottingham. Here he first drew an analogy between the falling of bodies to the earth and the inward curve of the moon in its orbit and suggested that both might be due to one and the same force. It may be remarked, in passing, that the story of an apple falling from a tree suggesting such a line of thought to Newton may have more truth to it than many other similar stories told about great men of the past.

It was not till over twenty years later that Newton published his universal law of gravitation in the monumental work now generally known as the *Principia*. This law states that any two bodies in the universe mutually attract each other with a force which can be found by multiplying their masses together and then dividing the result by the distance between them squared. This conclusion has been generally recognized as one of the crowning achievements of the human intellect, and its effects on the physical sciences were incalculable. The immense scope of this one law has made it possible to follow the progress of all celestial motions out to the limits of the observable universe, back into the distant past, and forward into the remote future. One of the most dramatic results was the discovery of Neptune in 1846. The pull of this unknown planet on Uranus made possible a calculation of its position, and this led to the recognition of Neptune as the eighth major planet in the solar system.

Astronomical observation may be divided into two great

epochs: the period of naked-eye observation and the period since optical and electrical instruments became available to aid the astronomer. It is important to remember that the developments leading to Newton's law of gravitation belong wholly to the epoch of naked-eye astronomy. And so we see the far-reaching results of Tycho Brahe's passion for accurate observation. Newton himself said: 'If I have seen further than others it was because I stood upon the shoulders of giants.'

The epoch of the telescope was ushered in when a Dutch spectacle-maker noticed that two lenses, held one in front of the other, made distant objects appear closer. Next year, in 1609, the same year in which Kepler announced his first two laws of planetary motion, Galileo turned his early crude telescope to the night sky. He immediately noticed that through the telescope one could see many stars that were invisible to the naked eye and that, while the stars themselves did not look appreciably larger, the planets appeared as tiny round disks.

During the next few months Galileo constructed improved telescopes, and new discoveries followed in rapid succession—mountains on the moon, the phases of Venus, spots on the sun, and, most notable of all, a system of four moons revolving about the planet Jupiter. This last observation proved, for all who would look, that the earth was not the centre about which all heavenly bodies revolved.

Let me digress here for a moment to explain the action of a telescope. The primary purpose of this instrument is to collect the light from a wide beam and concentrate it to a point called the focus. The most familiar example of this is a magnifying glass held in sunlight so that it forms a small hot spot that will burn paper or cloth. The lens of the telescope functions in the same way. It forms a small optical image of the object observed, and the larger the diameter of the telescope, the more light is collected, and the brighter this image will be. Also, the wider the original beam of light, the greater the detail seen in the image. Hence, both the image brightness and the detail seen depend on telescope diameter, or aperture. When a telescope is used visually a small lens called the eyepiece magnifies the image. A whole range of eyepieces with different magnifications can be used with any given telescope. Magnification is a secondary

property and will not materially alter either the faintness of the stars that can be seen or the detail observed on the moon and planets. If there is a choice, one usually finds that, under the normal observing conditions, the lower powers of magnification give the best results. In a photographic instrument the eyepiece is eliminated and a photographic plate placed at the focus *(Fig. 4)*.

Galileo's telescopes consisted of single lenses at either end of rolled paper tubes and had apertures of just over an inch and a half. He made most of his discoveries with an instrument nearly forty inches long which magnified about thirty-two diameters. The field of view was so small that less than one-quarter of the diameter of the moon could be seen at one time, and considering the imperfections of the early lenses and mountings it is surprising that so much was discovered with this equipment.

A simple lens bounded by spherical surfaces has two major defects: the light going through the outer zones of the lens does not come to the same focus as that going through the centre, and different colours of light focus at different positions. The first of these faults is called spherical aberration, and the second, chromatic aberration. Bigger telescopes soon followed Galileo's instrument, but attempts to avoid the imperfections of the single lens and the desire for high magnification encouraged telescopes which were of great length relative to their diameter. Unfortunately, progress was not as rapid as might have been expected, since the apertures remained small. A telescope three inches in aperture was generally over thirty feet long. By the end of the seventeenth century the Huygens brothers had constructed a monster telescope over 200 feet long, but its objective lens was only eight inches across, and it was so difficult to adjust and focus on the stars that it was seldom used. In the attempt to reach very high magnifications the importance of aperture was not yet fully realized.

During this period Isaac Newton and others suggested various ways of using a spherical mirror as a telescope. In this case no lens is required, since a concave mirror concentrates the light to a focus by reflection *(Fig. 4)*. Newton's original model of the reflecting telescope, presented to the Royal Society in 1672, can still be seen at Burlington House in London. But the construction of reflecting telescopes lagged for want of good material

from which to fashion the mirrors. Then one by one, starting early in the eighteenth century, came the discoveries which have made possible modern optical telescopes of both types.

An improved and very hard alloy of copper and tin was perfected for use in casting mirrors. The paraboloid was adopted instead of a spherical surface as the shape of telescope mirrors. Thanks chiefly to the work of Sir William Herschel, with his reflecting telescopes that ranged in size up to one four feet across, the importance of aperture was realized. And finally, a method of depositing a bright coat of silver on glass was devised. This eliminated once and for all the continual refiguring and repolishing that had been necessary with the old mirrors of metal. Glass mirrors could be figured with a surface accuracy close to a millionth of an inch and then coated with silver. Improved types of glass have made possible the 200-inch-wide mirror of the Hale telescope on Mt. Palomar. This mirror, the world's largest, weighs over fourteen tons. It is coated with a very thin layer of aluminum which reflects light more efficiently than silver and is used on most telescope mirrors today.

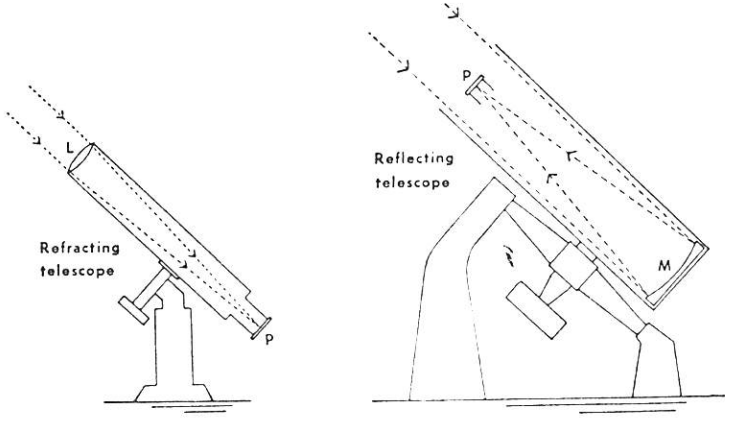


FIG. 4. The lens, L, or mirror, M, collects the light from a wide beam and concentrates it on the photographic plate, P.

To compare the light-gathering power of the 200-inch telescope with that of the unaided eye we must consider the diameter of the lens in the human eye. This can be taken as about one-fifth of an inch on the average. The diameter of the Mt. Palomar telescope is 1,000 times this and, since the light-gathering power goes as the square of the aperture, this great instrument collects roughly a million times as much light as the naked eye.

Improved refracting, or lens telescopes were made possible in the middle of the eighteenth century by the use of two different types of glass—crown and flint—put together to eliminate the worst of the aberrations. Later, the production of a great many types of improved optical glasses gave wide scope to the lens designs possible, and new methods of annealing glass resulted in very large disks. The objective lens of the refractor at the Yerkes Observatory near Chicago is forty inches in diameter, and this seems to represent the practical limit in size for a telescope lens. Further modern improvements have come through lens-mirror combinations and the use of optical surfaces which are far more complicated than the spheres and paraboloids of conventional instruments.

Telescopes are usually rated by the diameter of the objective lens or mirror. The amount of light collected will vary as the area of this optical unit, or as the square of its diameter. The bigger the objective, the fainter the stars that can be observed. The fineness of the detail seen also varies with the aperture, as already noted. If two light-bulbs were placed side by side one foot apart and you observed them with the 200-inch telescope, you could see them as separate objects from anywhere up to 1,700 miles away. This is the distance between Toronto and Edmonton.

Size alone is not enough to make a telescope a satisfactory observing instrument. The long monsters of the seventeenth century were so difficult to operate they could not be used on a routine programme. As early as 1845, Lord Rosse, at Parsontown in Ireland, had a reflecting telescope with an aperture of six feet. But this was very difficult to handle, and the great metal mirror needed refiguring every few years. Lord Rosse's instrument is now a museum piece.

In a modern telescope the design of the mounting and

auxiliary equipment is just as important as that of the telescope itself. In the case of the 200-inch telescope on Mt. Palomar, thanks to the engineering skill of those concerned, we have 500 tons of glass and steel that can be controlled by the touch of a little finger. A great telescope in its dome combines the bulk of a large office building with the precision of motion found in a good watch.

Up to the present I have said nothing about a discovery which, for the astronomer, is second in importance only to the invention of the telescope. I refer to the development of photography, without which most of our current knowledge of the universe would not have been acquired. The first astronomical photographs were taken in 1840 by Dr. J. W. Draper of New York, using the process invented the year before by Daguerre and known as daguerreotype. But it was not until the introduction of the dry plate, about 1880, that astronomical photography really came into its own. Since then it has steadily usurped the visual observing method, and today almost all serious research in the optical range of wave-lengths depends on photography for providing a permanent record. In a few special cases observations are made visually, or with the photoelectric cell, photomultiplier tube, and similar devices.

The great power of the photographic technique, and its importance to astronomy, lies in the ability of the photographic plate to add up the effects of the light falling upon it over a period of time. This means that if you can photograph stars down to a certain brightness with a given exposure time, by doubling this exposure time you can photograph stars down to roughly half the brightness of the previous limit. The relation is not strictly proportional, and limits are imposed by various factors such as sky brightness and the availability of the celestial object; but photographic exposures of very faint light sources have been extended successfully to over fifty hours in extreme cases.

When it is realized that what the eye sees is recorded almost instantaneously, even when using a large telescope, it is not hard to understand why we never observe visually the detail revealed in long-exposure photographs of the sky. The eye is also limited by its small size, about one-fifth of an inch as mentioned earlier,

while astronomical photographs of star fields and nebulae are generally taken on plates at least several inches across. Many people, when they visit an observatory to look through a telescope, expect to see something which is like the average picture reproduced in a good book on astronomy. What they actually do see is often very disappointing, especially if they have been waiting in line for some time before stepping up to the eyepiece.

Another important point to remember is that the photographic plate can be made sensitive to wave-lengths of light in the infra-red and ultra-violet, beyond the limits of the sensitivity of the human eye. Light in these regions of the spectrum often contains information unavailable when we are restricted to the visible region.

A major development of the astronomical telescope in recent years has been its extension to cover the range of radio wavelengths. It took between 200 and 300 years for the optical telescope to reach the status of an efficient observational instrument in the modern sense. On the other hand the first radio telescope was used by Karl Jansky at the Bell Telephone Laboratories only thirty years ago, yet powerful radio telescopes of top quality are already in use all over the world.

The sizes and shapes of these new radio telescopes vary much more than is the case with the optical instrument. The basic collecting unit is a dipole, an electrical conductor half a wavelength long. An everyday example of this is the television aerial you have on the roof. In the radio telescope the dipole is connected to a sensitive receiver, which normally includes amplification stages and a system for recording the strength of the received signal. A radio telescope may consist of a long row or bank of dipoles which are interconnected and feed into the same receiver. In this case the system is called an array. On the other hand, a dipole, or its equivalent, may be placed at the focus of a large concave radio mirror made of sheet metal or wire mesh. This is commonly called a dish. It concentrates the energy from a wide beam of radio waves much as the glass lens or mirror concentrates light in the optical telescope *(Fig. 5)*. A combination of the two types of radio telescope results when one or more rows of parabolic dishes are employed as an array.

Radio telescopes of the array type, nearly a mile in length, are

located at several observatories. The largest parabolic dish that is fully mounted so that it can be turned to any part of the sky, is at the Jodrell Bank Station of the University of Manchester in England. This dish is 250 feet in diameter. The U.S. Navy has under construction a similar instrument 600 feet across. In physical size alone, such equipment dwarfs even the largest optical telescopes.

The two chief functions of the radio telescope are the same as those of its optical counterparts: it collects and integrates radiation from across a wide beam and reveals fine detail in the source studied. The greater the area of the beam, the higher the power of the recorded signal. Also, the bigger the radio aerial system, the more detail seen. These rules parallel those for optical equipment.

Big as they are, the radio telescopes cannot reveal nearly as much detail as the optical instruments. The capacity to reveal detail depends basically on the ratio between the size of the tele-

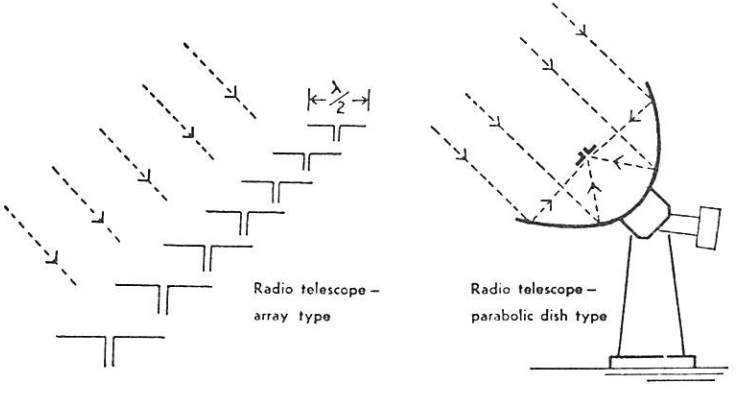


FIG. 5. Radio waves are collected by units half a wave-length long (half-wave dipoles) connected to a sensitive radio receiver. A large parabolic dish may be used to concentrate a beam of radio waves onto a collecting unit.

scope and the length of the light waves or radio waves being recorded. Optical telescopes are millions of times bigger than light waves; but the best radio telescopes are only several hundred times bigger than radio waves. And yet the radio telescope can probably record objects more distant than any within reach of the optical telescope. Each type of instrument complements the other.

From what I have said earlier, it is evident that man did achieve significant results in his study of the physical universe through observations made with the naked eye alone. But the astronomer of today is dependent on many types of ingenious instruments, equipment especially designed to unlock the secrets of space. Now we are commencing to operate these instruments out in space itself, beyond the earth's atmosphere. Our air, necessary as it is for the support of life, absorbs many of the radiations from space and prevents them from reaching the surface of the earth. Artificial satellites outside the atmosphere make possible remotely controlled astronomical observations, using ultra-violet, infra-red, and radio waves that we have never been able to record in the past. In this new age of astronomy the instrument observes, man interprets.

OUR NEIGHBOUR WORLDS
2

MOST of the matter in our universe exists in the form of very hot gas, making up the stars, or as much cooler gas and dust, scattered through space. A very small fraction is in the form of dark, relatively cool, solid bodies I shall call worlds. There is no particular reason why there may not be countless numbers of such worlds out among the stars, but with our present instruments we cannot observe or even detect them. Our discussion is therefore limited to our own family of worlds, the members of the solar system held by the sun's gravitation in a local group.

I have called these our neighbour worlds and the term is apt in spite of their great distances. To illustrate this, suppose we make a scale model where the distance from the earth to the sun, ninety-three million miles, is just under one-quarter of an inch. Now take a dime out of your purse. On the scale of our model the orbits of the four inner planets Mercury, Venus, Earth, and Mars, fit comfortably on this coin with the orbit of Mars represented by the circumference. The orbits of all four planets are very nearly in the same plane, and it so happens that the thickness of the dime represents to scale the thickness of the disk-shaped volume of space within which these planets move *(Fig. 6)*. The orbit of Neptune, the outermost large planet, will be fourteen inches across centred roughly on the dime and also nearly in the same plane. It is only when we come to little Pluto, with an orbit a bit bigger than Neptune's, that we find its orbit tilted by quite an angle to the rest

(Fig. 7). All the planets move round the sun counter-clockwise as viewed from the north. And on the scale of our model where will the nearest star be? Exactly one mile away from the dime. This is the closest star. The centre of our star system, or galaxy, would be over 6,000 miles from the dime, and the millions of other galaxies very much further away. I think you will agree that the term neighbour worlds is quite appropriate.

These worlds fall naturally into four groups, a division based in general on size and orbital characteristics. In one group are the four inner planets Mercury, Venus, Earth, Mars, and, at the outer edge of the planet orbits, Pluto. All but distant Pluto have been known from antiquity. They can conveniently be called the earth planets, since they resemble our own home planet more closely than does anything else we have found in space. Their diameters range from 3,000 to 8,000 miles *(Fig. 8).*

Then we have the four great planets, Jupiter, Saturn, Uranus, and Neptune. These have average diameters ranging from 27,000 to 87,000 miles, roughly ten times those of the earth planets, and their orbits lie in the outer part of the solar system.

The next group of worlds consists of the moons, or satellites. These are, in general, smaller than the planets and move in orbits about the planets. In all, thirty-one natural satellites of six planets are known. The Earth, in addition to its one satellite of natural origin, has a rapidly growing complex of artificial satellites.

The last of the four groups of worlds is that of the asteroids. These little planets have orbits which form a network, mainly between the orbit of Mars, at the edge of our dime, and the orbit of Jupiter, one and a quarter inches from the dime centre. The orbits of over 1,600 asteroids have already been tabulated. There are probably some 50,000 of these little worlds in all.

Let us visit each of the four groups of worlds in turn, starting with the asteroids. The first asteroid was discovered in 1801, and was called Ceres. It is the largest of the group, having a diameter just under 500 miles. In the period from 1802 to 1807 three more asteroids were discovered. But the fifth was not found until 1845 and it was only after the introduction of photography that the little planets were found in large numbers each year.

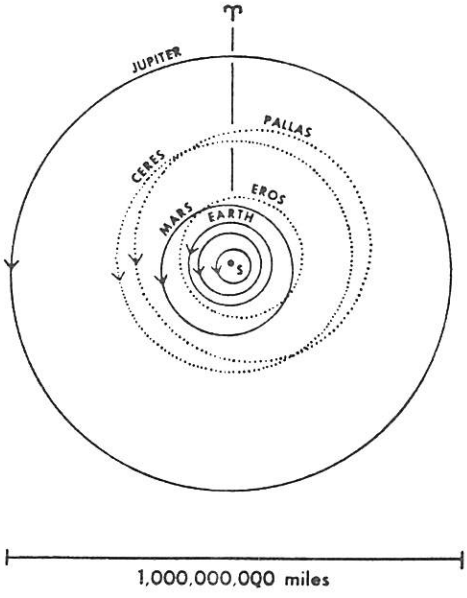


FIG. 6. The orbits about the sun, S, of the inner planets, three asteroids, and Jupiter. The vertical line indicates zero longitude, or the first point of Aries, whose symbol is the horns of the ram. The scale here is the same as suggested in the text, where the orbit of Mars fits on a dime.

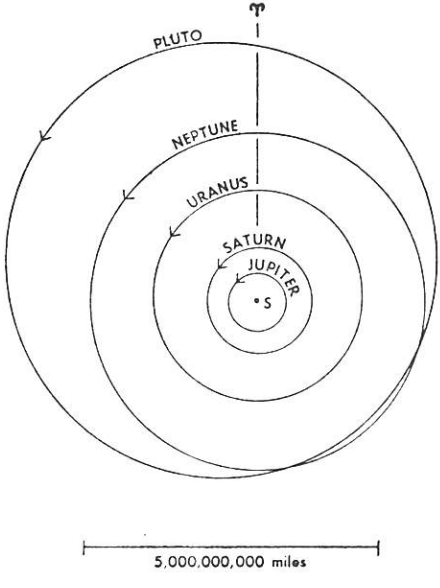


FIG. 7. The orbits about the sun, S, of the outer planets. Pluto's orbit is inclined 17° to the plane of the paper.

The great problem is to keep them all sorted out. In most cases the only sure identification is the position of the orbit around the sun. Even after these orbits have been determined it requires a great deal of work to keep them up to date, since they change slowly as a result of the gravitational pull of the large planets, in particular Jupiter. Asteroids are often lost owing to the impossibility of following them all.

The discoverer of an asteroid has the privilege of naming it, and by tradition most of these objects are given feminine names. When the orbit is unusual a masculine name is given. At first, asteroids were given names taken mainly from classical mythology. But these names were soon used up, and now we find little planets called Jenny, Hilda, Ruth, Marilyn, Susanna, and Alice, to take a few modern examples. One of the most extreme orbits is that of Icarus, aptly named after the youth who singed his wings. This asteroid swings in closer to the sun than the planet Mercury.

The great majority of asteroids are quite small. Less than twenty have diameters over 100 miles, and most of those discovered to date are in the ten- to fifty-mile category. The smallest known are about a mile across. Except for the largest members of the group the asteroids seem to be quite irregular in shape, and show a variation in brightness as they rotate in periods of a few hours. One famous asteroid, Eros, came close enough to the earth in 1931 for its shape to be observed in the telescope. Eros is a piece of rock, eighteen miles long and five miles wide, and it turns end over end in a period of 5¼ hours. These jagged lumps of space rock seem to be fragments of one or more medium-sized planets that must have broken up when the solar system was much younger.

The surface gravity on these little worlds is extremely weak ranging from one-hundredth to one-thousandth of the earth's surface gravity, and even less for the smallest asteroids. It would not be difficult to throw a stone right off into space from an asteroid ten or twenty miles across. In fact, you would have to be careful not to jump too hard on a very small asteroid, or you might find yourself unexpectedly launched into space. No asteroid has a force of gravity strong enough to retain an atmosphere of any kind.

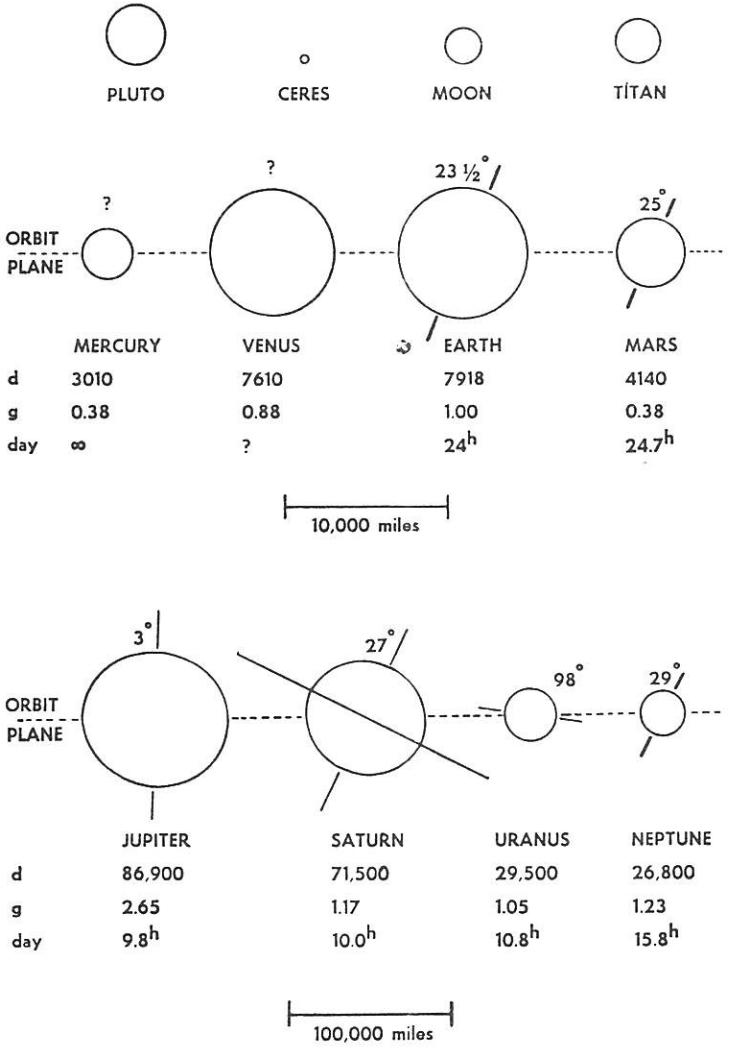


FIG. 8. The relative sizes of the planets plotted to scale; d = mean diameter in miles, g = surface gravity in terms of earth's. The length of each planet's day is given in terms of hours on the earth; the angle between a planet's equator and its orbit is given in degrees. For additional planetary information see Appendix A.

The satellites, which make up the next group of worlds, range in size from the two little moons of Mars, five to ten miles across, up to the two largest of the twelve moons of Jupiter. These Jovian satellites are well over 3,000 miles in diameter, and thus bigger than Mercury. The smallest of the satellites, on the other hand, are much like the asteroids, in fact some of them may have been asteroids before being picked up by the parent planet.

As an example of the larger satellites we can take our moon, which is close enough to be studied in some detail. The diameter of the moon is just over 2,000 miles, not far from one-quarter the diameter of the earth. Its mass is roughly one-eightieth of the earth's mass and its distance thirty earth-diameters, or about 240,000 miles. Absence of an atmosphere on our satellite gives a hard, sharp contrast between light and shadow. This is particularly striking when the sun is low in the lunar sky and shadows are very long, greatly exaggerating the rugged character of the surface detail.

The world of the moon may be visited by space travellers within a reasonable period of time. The absence of atmosphere means a dark sky full of stars, even with the sun above the horizon. It is a silent world as no air waves carry the sound of wind or weather, and surface gravity is low, about one-sixth that on earth. On the moon a 200-pound man would be a light-weight of only thirty-three pounds. The surface is covered with a dusty, grey-brown, ashy substance, that stretches in gentle rolls out to the horizon. And the horizon on the moon seems unusually close, a consequence of the high curvature of the lunar surface.

A day on the moon lasts for 29½ of our days. The sun slowly rises and slowly sets, and all this time the earth appears to remain nearly stationary in the sky, a great, bluish-white globe, four times as wide across as the sun. The moon keeps the same face always towards the earth so that from most positions on the lunar surface the earth will not appear to rise or set, and on the far side of the moon the earth can never be seen.

There is a very large temperature range between day and night conditions on the moon. When the sun is high the surface

temperature rises to over 200° Fahrenheit. At sunset this drops to 50° below zero, and in the middle of the long lunar night it may be colder than 300° below zero.

On the moon's surface we find long mountain ranges with some peaks higher than Mt. Everest, deep valleys, low undulating ridges, and long cracks or crevasses. Steep slopes are uncommon and the dark surface material is fairly smooth on a scale of inches—a rather surprising fact revealed by radio observations. The most characteristic feature of the entire lunar surface is the presence of thousands of circular mountain forms called craters. These vary all the way from the smallest we can observe, a fraction of a mile across, up to some over 150 miles in diameter. The lunar craters do not resemble volcanic craters, and it is unlikely that enough volcanic activity could exist on the moon to produce all the craters found there. But localized emissions of gas probably still occur from time to time. An event of this type was photographed in the crater Alphonsus on November 3, 1958, by N. A. Kozyrev at the Crimean Astrophysical Observatory. Most astronomers now believe that the majority of the large lunar craters resulted from the impact of great meteorites in the far distant past of the solar system.

The absence of an atmosphere on the moon is not surprising, since the moon's surface gravity is not enough to hold the common atmospheric gases under temperature conditions corresponding to the lunar surface. The largest satellites in the outer part of the solar system, where it is colder, should be just able to retain an atmosphere. In fact methane, or marsh gas, has been detected on Titan, the largest satellite of Saturn. In passing, you may wonder how we know what is in the atmosphere of a distant heavenly body. The light emitted or reflected by atoms and molecules frequently contains certain characteristics peculiar to the elements involved. When this light is analyzed by the spectroscope, the substances in the source can be named with certainty.

We move on now to the four giant worlds, Jupiter, Saturn, Uranus, and Neptune, with equatorial diameters ranging up to 90,000 miles. If we represent the earth by a large marble, or agate, then Neptune would be the size of a baseball, and Jupiter a basketball. In spite of their size these great planets all spin

rapidly on their axes with rotation periods of less than sixteen hours. Jupiter, the largest, has the most rapid rotation, turning once in under ten hours. A point on Jupiter's equator moves eight miles a second, fast enough to throw loose material off into space under the gravity conditions we find on earth. But the Jovian surface gravity is over two and a half times that found here, so there is no danger of this planet showering space with loose surface material.

The rapid spin does have the effect of flattening these planets at the poles. Jupiter has a polar diameter 6,000 miles less than its equatorial diameter. The chief surface markings visible are great cloud belts drawn out along lines parallel to the direction of rotation. The various cloud belts of Jupiter, and semi-permanent features floating in the belts, have rotation periods that differ slightly from each other. For example, the Great Red Spot has been well observed for over one hundred years, and may have been seen as early as A.D. 1664. It has its own rotation period that varies somewhat from the rotation periods of the belts.

One of the more interesting recent discoveries has been the detection of radio noise from Jupiter. This may originate in atmospheric disturbances or storms of some type, and is usually observed at wave-lengths from ten to twenty metres. Much of it seems to originate from localized centres that have been tentatively identified with some long-enduring markings in the cloud belts. Perhaps free-floating storm centres have some way of maintaining themselves or, alternatively, these centres may be tied to a solid surface below the clouds.

The spectroscope shows that the clouds of Jupiter consist of methane—the same gas that was found in Titan—mixed with ammonia. All four planets have methane present in large quantities, but only Jupiter and Saturn show ammonia clearly, while Uranus may have a very faint trace of it. To find an explanation for this fact we take a look at the surface temperatures. Measured values on the Fahrenheit scale range from 210° below zero for Jupiter, down to 330° below zero or lower for Neptune. At these temperatures ammonia freezes while methane would remain a gas over most of the range. Apparently on Jupiter we have frozen crystals of ammonia

floating in a methane atmosphere. As we move out to the colder temperatures of the outer planets we find that most of the ammonia has disappeared out of the atmosphere, leaving only the methane which becomes progressively stronger. Heavy layers of methane absorb red light, giving Uranus a greenish colour and making Neptune look blue.

Obviously, in the case of all four of these planets, we see only the outer layers of a very extensive cloud cover. The low mean densities, not much greater than that for water, suggest that a large part of the volume of each planet must consist of the atmosphere, which is probably hydrogen and helium, together with carbon and nitrogen compounds. Under these conditions one would not expect to find free oxygen, for it would combine with the hydrogen or other elements.

One theory about the interiors of the giant planets is that each has a small rocky or metallic core at the centre, surrounded by a deep ice layer. Recently, however, it has been pointed out that hydrogen and other light elements will act like metals under the extreme pressure found in the interior of such planets. Possibly the denser cores are merely hydrogen under high pressure.

All the great planets are well supplied with satellites, and Saturn has, in addition, a unique system of rings that circle the planet well inside the orbits of its nine moons. These make it one of the most beautiful telescopic sights in the heavens. The rings, which are 170,000 miles across but only about ten miles thick, consist of countless small solid particles revolving about the planet. The light reflected from the rings seems to suggest ice particles, mixed probably with stony material. No satellite of any size could exist in the position of the rings; it would be torn apart by tidal forces.

I have left to the last the five small earth planets: Pluto, Mars, Earth, Venus, and Mercury. Pluto, on the outer edge of our system, is so far away that we know very little about its physical condition. Even its diameter is not well determined, but is probably about half that of the Earth. This is too small to retain the lightest gases and the others, if present, are probably frozen on the planet's surface. The temperature must be about 350° below zero Fahrenheit.

Mercury, at the other extreme from Pluto, is close to the sun—a scorched little world that hurries around its orbit once every eighty-eight days. Like our moon, which keeps one face to the earth, Mercury always turns the same side to the sun. The temperature at the centre of the sunward face averages 660° Fahrenheit—hot enough to melt lead. In contrast, the central part of the dark hemisphere on Mercury is never exposed to sunlight and the temperature here is estimated as 410° below zero—colder even than the daylight side of Pluto. Mercury has no atmosphere to moderate these terrible extremes of temperature.

Apart from the Earth only two worlds remain to be discussed: Venus and Mars. These are the two planets closest to the Earth in space and also in size, and here we find physical conditions which most nearly parallel those in which we live.

Venus, 7,600 miles in diameter, is almost the same size as the Earth. It revolves about the sun once every 225 days in an orbit just inside ours. Thanks to the smaller size of its orbit, and a greater speed in this orbit, Venus laps the Earth every 584 days or 19½ months. This is a useful period to remember, since it represents the interval between successive returns to the same relative positions for Earth, Venus, and Sun. For example, if a certain situation is particularly favourable for a space flight to Venus, essentially the same situation will repeat itself just 584 days later. A flight to Venus under minimum power conditions takes 146 days, and a shorter time if extra power is available.

And what are we likely to find on Venus? The length of its day is not yet known with any certainty, but this is probably a few weeks. Thick clouds of carbon dioxide rise to heights of some twenty miles above the surface, hiding its nature from outside view. Clouds of this type should have a strong heating effect, and this is confirmed by recent radio measures of the surface temperature, which give a value over 500° Fahrenheit, almost as warm as Mercury. This temperature drops by some 25° for every mile you go up, until at the top of the cloud layer it has reached a reasonable 50° to 60° Fahrenheit. The atmosphere of Venus probably contains nitrogen, and perhaps as much as one-quarter consists of this element. Traces of water

vapour have also been detected. It seems likely that the atmospheric pressure at the surface of Venus is high by terrestrial standards, possibly ten or twenty times the sea-level value on Earth. The above summary indicates a most inhospitable environment awaiting the first contact from Earth.

On Mars, in contrast to Venus, we find an atmosphere that is thin and quite transparent so that the solid surface of the planet is visible. Also, Mars revolves about the sun in an orbit outside that of the Earth, which means that when we are closest to this planet we are looking at its daylight hemisphere. Although Mars is just 4,200 miles in diameter, it closely resembles the Earth in a number of ways. The day on Mars is forty minutes longer than ours. The tilt of its equator to the orbit-plane is almost the same as the Earth's, which results in seasonal changes similar to ours. However, it takes Mars 687 of our days to go once about the sun, so its seasons are nearly twice the length of our seasons. We overtake Mars at intervals which average two years and fifty days. Mars is then said to be in opposition, that is opposite to the sun in the sky and closest to the Earth. The last opposition of Mars was on December 30, 1960. The next will be in the middle of February, 1963. Since the orbits of Mars and the Earth are not circular, we may be as much as sixty-three million miles from Mars at some oppositions, and only thirty-five million miles away at others.

The most evident surface features on Mars are the two white polar caps. During the Martian winter season in either hemisphere, these may extend down to a latitude of sixty degrees, or roughly one-third of the distance from the pole to the equator. They become very small or disappear entirely in late summer. Measurement of the temperatures at the polar caps strongly supports the suggestion that the white material is some form of snow or frost. As spring advances this evaporates into the thin atmosphere of Mars, while at the peak of the evaporation period a narrow band of water forms along the border of the shrinking cap. The maximum thickness of the snow or frost is probably not more than two or three inches.

As the south polar cap shrinks during spring in the southern hemisphere certain areas on the Martian surface start to grow darker. The effect appears first in the south polar region, but

spreads down towards the equator and into the opposite hemisphere as spring advances. Towards the end of the southern summer there is a general fading of the dark areas. This is followed by another wave of darkening, proceeding from the north polar regions this time, as the north polar cap melts. The conclusion seems inescapable that these seasonal changes on Mars result from the periodic release of extra moisture into the normally dry atmosphere. The colour of the dark markings has frequently been described as green, but it is believed that much of this impression of a green colour results from contrast with the red-orange shade of the remainder of the Martian surface. The true colour of the dark areas is more likely a bluish-grey.

The so-called 'canals' of Mars, long, narrow, dark markings first observed by Schiaparelli in 1877, have been plotted in various forms by most observers of the planet. Over the last eighty years there has been a continued and lively discussion among astronomers about their exact nature. I can sum up the present situation by saying that there is general agreement on the reality of the canals, in other words they are not illusions, but result from something on the Martian surface that produces the effects drawn by the visual observers and recorded on the photographs. The big question is: Are they continuous, essentially uniform in width, and geometrically straight, which would suggest an artificial origin; or are they made up of a maze of irregular fine detail which blends into a line-like image under our difficult conditions of observation? This latter alternative suggests a natural origin. Here we find widely divergent views, but most astronomers feel that the second alternative is more likely.

I can speak more confidently about some of the other aspects of the Martian surface. Gravity is thirty-eight per cent, that is about a third, of the value on Earth. The atmospheric pressure at the surface is just one-twelfth of our sea-level value, and corresponds to the pressure about ten miles above the Earth. But at heights near twenty miles the pressure is the same on both Mars and the Earth, about an eightieth sea-level pressure. Above this, Mars actually has a denser atmosphere than the Earth has at corresponding heights.

The Martian atmosphere is predominantly nitrogen with two or three per cent carbon dioxide, possibly a little argon, and very small traces of water vapour and oxygen. The temperature on the night side of Mars drops to 50° or 100° below zero Fahrenheit, but as the sun rises over the equatorial regions the surface rapidly warms up, and by ten o'clock in the morning it is above freezing, reaching a peak of about 70° near midday. Yellow dust clouds are sometimes observed two or three miles above the Martian surface. Above these we have a violet haze-layer, extending up to about ten miles. This haze normally covers most of the planet, but may suddenly clear off in a most unaccountable manner. The nature of the phenomenon is not yet understood. Above the haze, we sometimes see white or blue clouds, probably ice crystals.

What about the possibility of life on these other worlds? Suppose we consider for a moment the physical conditions under which life normally exists. Throughout the universe we have some ninety-two natural elements, with the same properties as found here on Earth. Organic matter, as we know it, is built up of very complicated molecules consisting chiefly of the four elements hydrogen, carbon, nitrogen, and oxygen. In this system carbon is the key element and forms the backbone of the long chains of atoms combining to make up various organic molecules. Only one other element, silicon, seems to be a possibility as a substitute for carbon in the building of life-molecules, but this is a pure supposition and we have no evidence of this hypothetical 'silicon-life'.

To maintain our terrestrial type of 'carbon-life' we must have some readily available form of energy, and temperatures below 150° Fahrenheit—that is, low enough to permit the continued existence of very complex molecules. There should also be carbon dioxide to supply carbon and water or water vapour to provide moisture. This last condition presupposes temperatures high enough to melt ice, but this need only be for a fraction of the time, since presumably life can lie dormant for long periods of extreme cold. Finally there should be an absence of toxic substances such as ammonia, methane, carbon monoxide, and chlorine.

In considering the possibility of organic life on our neighbour

worlds we can rule out at once all the little worlds without atmospheres and all the cold giant planets, or large satellites, with extensive but poisonous atmospheres. This leaves only our two immediate neighbours Venus and Mars, both of which lie in the temperature zone capable of supporting active life. If our present understanding of the surface temperature of Venus is correct, there seems small chance of life forms anywhere near its surface, and it would appear rather doubtful that life could exist only near the top of the cloud layer.

On Mars the situation is different. Here the regular seasonal changes in the dark markings seem best explained by some form of vegetation. Admittedly this does not show the chlorophyl characteristic of the green colouring matter in plants, but the Russian astronomer G. A. Tikhov has pointed out that vegetation on Earth, which grows in cold, high-altitude regions, often lacks this chlorophyl characteristic also. In 1956, W. M. Sinton of the Lowell Observatory, working with the 200-inch telescope on Mt. Palomar, analyzed the light of Mars in the infra-red. With the spectroscope he found that the dark areas on Mars reflected light with features in the infra-red which corresponded to those found in light reflected by certain vegetation on Earth. This gave evidence for the presence on Mars of organic molecules, and in particular, of carbohydrates. However, there was no indication of the presence of these organic features in the light from the orange-red desert regions of Mars.

Although we must be careful not to be too positive, I think most scientists agree that this recent work points strongly to the existence on Mars of some drought-resistant type of vegetation, which revives rapidly from a dormant state when the polar frosts distribute moisture over the Martian surface. And so far as I know, this, together with the other phenomena of the Martian surface, is the only well authenticated and positive evidence we have for the existence of organic life elsewhere than on Earth.

VISITORS FROM SPACE

3

IN the last few years the idea of man sending something out into space has become almost commonplace. Even the concept of space travel is accepted as a matter of course.

But here I want to discuss the visitors that, over millions of years, have been coming to the earth from space. I refer to the countless numbers of solid particles that drop daily into the earth's atmosphere. These are the meteoritic debris of the solar system, and they range in size all the way from tiny grains of sand up to large crater-producing objects many tons in weight. The arrival of the latter can make the explosion of a hydrogen bomb seem small by comparison.

Let us look first at the space dust that falls in a continuous shower on the earth's surface. This consists of solid particles of nickel-iron and other elements. The diameters range from 0.0001 inch to 0.01 inch, and you can take 0.001 inch as a good representative size. How do we detect this silent unseen shower from space?

There are several quite independent methods for studying it. Evidence for non-terrestrial material is found in the residue of melted arctic snows, in samples taken high above the earth by aircraft and balloons, and in the dredgings from the deposits in the depths of the oceans. Another detection method is to record the impacts of this dust on the surfaces of rockets or artificial satellites. Here very sensitive acoustical equipment can be used, or highly polished plates can be placed on the rocket surface, and the subsequent pitting measured. All methods lead

to essentially the same estimate of the daily total of this space dust which falls upon the earth, and the answer may surprise you. Day in day out, year in year out, between 1,000 and 10,000 tons of matter in this form are added to the earth each day. However, even this large amount, falling continuously for 1,000 million years, has totalled less than a millionth of the mass of the earth.

These very small dust particles collide with the upper atmosphere of the earth at speeds from ten to thirty miles per second, but they are slowed down without being vaporized or becoming luminous. Heat caused by friction with the atmosphere is radiated away so quickly that the particles never become very hot.

When we move up the scale and consider the larger particles, with diameters 0.1 inch or more, the situation is very different. Here the surface of the particle is vaporized by collision with the air molecules, the energy of motion is converted into light and heat, and we see a streak of luminosity called a meteor or shooting star. Of course the resemblance of a meteor to a star that moves is superficial only, as stars and meteors are completely different in their physical properties.

Something like 200 million visible meteors enter the earth's atmosphere daily, but the total weight of all these particles is very much less than the weight of space dust that falls in a day. A single observer, watching the sky on a dark night, will normally see about five meteors an hour before midnight, but ten or more meteors an hour during the last half of the night. The increase in numbers for the early morning hours results from the fact that the earth is moving at a speed of eighteen miles a second around the sun. After midnight, thanks to the rotation of the earth on its axis, the observer is located on the forward side of the earth and more meteors are encountered. For an example of this effect imagine yourself running in the rain. Your front will encounter more rain drops, and become wetter, than your back.

The speed with which meteors encounter the earth has been determined by various photographic and radar techniques. If you take a photograph of a meteor with a simple camera, you have a straight continuous line on the negative. If, however, a

rotating shutter, something like a fan blade, is placed in front of the camera lens, the straight-line image of the meteor will be broken up into segments, a break occurring every time the lens is covered. Now it is only necessary to know the frequency with which the shutter covers the lens to calculate the speed of the meteor's motion across the sky. If two photographs are taken from points twenty or thirty miles apart, the distance of the meteor can be found by triangulation, and from that the actual velocity in the atmosphere is known.

Practically all measured meteor velocities lie in the range between ten and forty-five miles per second, with a particular preference for slow velocities near fifteen miles per second, and fast velocities near forty miles per second. The slow group

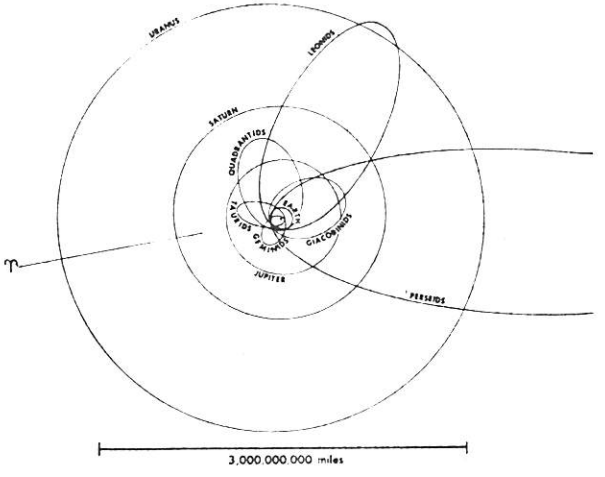


FIG. 9. Typical orbits of some of the better-known meteor showers. To show their true shape these meteor orbits have been plotted in the same plane as the planet orbits. Actually the meteor orbits are highly inclined to the planet orbits—by angles which average 70° for the examples shown here.

represents the meteors that are overtaking the earth, the fast group those meteors which the earth runs into head on. There is a similar difference between rear-end collisions and head-on collisions on the highway.

The upper speed limit of forty-five miles per second, found as a result of the accurate observation of thousands of meteors, tells a significant story about the possible origin of these objects. This speed is the fastest at which any body, moving in a stable orbit around the sun, can collide with the earth. If we found a meteor travelling appreciably faster than this, we would have to conclude that it had come from space far beyond the solar system. Since meteors enter our atmosphere at speeds less than this critical limit, it is a pretty good indication that they are all members of the sun's family and have an origin associated with that of the planets, comets, and satellites. In fact the orbit of any well observed meteor can be calculated, and such orbits are found to be ellipses, mostly quite elongated *(Fig 9).*

These orbits bear a close resemblance to those of the periodic comets, objects which appear from time to time in our night sky, often with one or more beautiful curved tails. The best known periodic comet is Halley's comet that returns to the vicinity of the earth every seventy-five or seventy-six years. Its last return was in 1910 and it is expected again about 1986. In spite of a close physical connection between comets and meteors one should not confuse the two observationally as they are quite different. A comet when seen is far beyond the earth's atmosphere and may be visible for several weeks or even months. A meteor, on the other hand, is only visible when moving quickly within the atmosphere, is not often seen for much longer than a second or two and, as it vaporizes, it terminates its existence as an individual celestial body.

Certain groups of meteors are found to be travelling along orbits which are identical with the paths of well known comets. The meteors are scattered widely along these orbits, and when the earth passes across one of these highways in space it collides with millions of objects, all moving along parallel paths *(Fig. 10).* This is called a meteor shower. To an observer, parallel lines seem to meet in the distance, an effect of perspective. Parallel meteor paths meet in the same way. Hence, when

meteors belonging to the same meteor shower are plotted on a star map, their apparent paths all converge to a point in the sky called the radiant. This marks the direction from which the meteors have come. A meteor shower in August has its radiant in the direction of the constellation Perseus, and this is called the Perseid meteor shower, while in the middle of December we have the Geminid meteors, with a radiant in Gemini. Some of the best known meteor showers are listed in the table, shown on page 35.

At the time of a meteor shower more meteors than normal are visible to the naked eye. There have been occasions in the past when the number of shooting stars was so great that it caused a considerable amount of public comment, not to mention fear and panic. One of the most noted of such phenomena was the spectacular Leonid shower on the morning of November 13, 1833. Let me quote an eye-witness account from an observer at Niagara Falls:

> An incessant play of dazzlingly brilliant luminosities was kept up in the heavens for several hours. The wild dash of the waters as con-

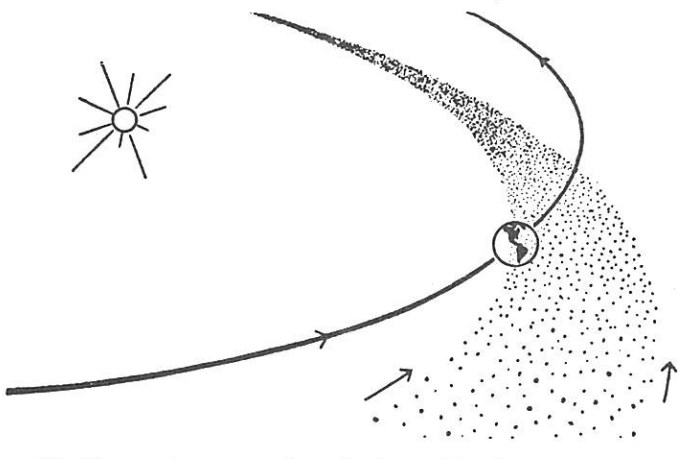


FIG. 10. The earth passes through the orbit of a meteor shower.

trasted with the fiery uproar above them formed a scene of unequalled sublimity. In many districts the mass of the population were terror-struck, and the more enlightened were awed at contemplating so vivid a picture of the Apocalyptic image—that of the stars of heaven falling to earth.

You can see, from this quotation, that the phenomenon was an exciting event.

The finest meteor shower we have had over North America in the twentieth century was the Giacobinid (or Draconid) shower on the night of October 9, 1946. On this occasion a single observer could count twenty meteors a minute in spite of the brilliant moonlight. The sky was overcast at many points in Eastern Canada, but I was fortunate enough to make observations from North Bay, where it was clear, and we recorded over 2,000 meteors in a four-hour watch. These meteors were travelling along the same path as the comet Giacobini-Zinner. This comet has a period of 6½ years and has appeared twice since 1946; but unfortunately the meteor shower has been deflected so that its centre now misses the earth's orbit, and we see only a few scattered remnants.

The shooting stars belonging to the spectacular showers, and also most of the others seen on an average night, seem to be so closely connected with the comets that they may be regarded as cometary fragments and referred to as cometary meteors. They dissolve into dust and vapour when subjected to moderate pressure and we conclude that the physical structure is fairly fragile, and possibly porous. It is an interesting fact that no example of a cometary meteor is known to have reached the earth's surface, except as dust.

Not all visible meteors are of the cometary type. A small percentage have a different origin and appear to be fragments of planets. They are closely allied in orbital characteristics to the minor planets, or asteroids, hence the term asteroidal meteor. I will come back to this group a little further on.

Why does a meteor become luminous in the atmosphere? Until its contact with our upper air, it is a relatively cold, dark body. However, travelling at tens of miles per second, its energy of motion is high, since this goes up in proportion to the square of the velocity. As the particle enters the atmosphere it collides with the air molecules, and meteoric atoms and

molecules are broken off. Further collisions with the air excite this mixture of air and meteoric atoms so that it shines with the characteristic light of the atoms involved. If we analyze the light of meteors with the spectroscope we recognize the yellow-orange light of sodium, the green light of magnesium, two monochromatic violet hues due to calcium, and a whole series of radiations of various colours coming from silicon and iron atoms. In the infra-red portion of the spectrum the light of oxygen and nitrogen is prominent. Such information gives us a clue to the physical reactions involved when a solid particle moves at high speed through a gas of low density.

Very bright meteors are called fireballs. There is probably no natural phenomenon of the heavens more spectacular than the arrival of a brilliant fireball. The brightness of these objects can rival that of the full moon and, in extremely rare cases,

TABLE OF METEOR SHOWERS

Meteor Shower	Date of Maximum	Duration in Days	Associated Comet	Remarks
Quadrantid	Jan. 3/4	0.6		Good annual shower of short duration.
Lyrid	Apr. 21/22	2	1861 I	Weak shower.
Delta Aquarid	Jul. 29/30	20		
Perseid	Aug. 11/12	5	1862 III	Strong annual shower.
Giacobinid	Oct. 9/10	0.1	Giacobini-Zinner	Great displays in 1933, 1946.
Orionid	Oct. 20/21	8	Halley	
Taurid	Nov. 4—12	40	Encke	No marked maximum.
Leonid	Nov. 16/17	4	1886 I	Great displays in 1833, 1867.
Geminid	Dec. 13/14	6		Strong annual shower.

approach the luminosity of the sun. The head of a fireball often appears like a tear drop in shape. This trails a long tail of light that may show all the colours of the rainbow, while red and yellow sparks drop off as it passes across the sky. In many instances the motion of these fireballs is slower than in the case of the average meteor. Most of the brighter fireballs are asteroidal meteors. They move around the sun in the same direction as the earth, so that when they enter our atmosphere they are usually overtaking us. This accounts for their slow speed across the sky.

In general meteors are visible about sixty miles above the surface of the earth. But when a meteor is slow enough and bright enough it may come down to heights of only twenty or thirty miles. Here the air will carry sound waves, and fireballs reaching these levels can sometimes be heard. Since the meteor is travelling well above the velocity of sound it forms a sonic shock-wave, and this is heard on the ground as one or more detonations or explosions, hence the term detonating fireball. Since sound takes about five seconds to travel a mile, the detonations produced by a fireball generally arrive at the ear of the observer several minutes after the visible phenomenon has taken place. The explosive sounds may be followed by a prolonged rumble, which is produced by the air falling back into the vacuum left immediately behind the fireball's head. Detonating fireballs are almost certainly of the asteroidal type, as cometary meteors are so fragile that they disintegrate above the levels where sound is transmitted.

A portion of a large asteroidal meteor may fall to the earth as a solid object and is then called a meteorite. Here we have an actual sample of material that has come to us from out among the planets. How many meteorites fall each day? It is difficult to give a good estimate and various authorities have suggested values between five and thirty meteorites per day for the whole earth. Certainly the great majority of meteorite falls are never recorded. For example, Canada and the U.S.A. are roughly the same size but, while some 600 different meteorite falls have been recovered in the United States, only twenty-six falls are known for Canada. Both countries probably receive about equal numbers of meteorites from space. The

difference in recorded numbers results from the fact that far more people live in the United States than in Canada, and the U.S. population is more evenly distributed than the Canadian population. Thus there is a much greater chance of someone observing the fall of a meteorite in the United States.

A recent Canadian meteorite fall occurred just north of Edmonton near the small settlement of Bruderheim. At 1.06 a.m. on March 4, 1960, a very brilliant fireball was seen travelling in an easterly direction over central Alberta. The large stone forming the nucleus of this spectacular object broke up high in the atmosphere, and its fragments were scattered over a large oval area several miles across. Many hundreds of individual pieces have been recovered with a total weight of over 600 lb. It is quite likely that the original object weighed at least 1,000 lb. before it entered our atmosphere.

Most of the individual pieces from this fall have been collected at the Department of Geology of the University of Alberta. Members of the University staff are making a study of the stones and the circumstances of the fall. On a recent visit to Edmonton I was able to examine these specimens, which represent the largest amount of space material yet recovered from one fall in Canada. The material itself is a light grey in colour, but if a lens is used one can see small bright flecks in the grey stone. These are pieces of metallic nickel-iron. Most meteorites contain greater or lesser amounts of this alloy, a feature which distinguishes them from our terrestrial rocks.

Freshly fallen meteorites are covered by a dark, fairly smooth crust, about one-hundredth of an inch thick. This is formed when the melted surface of the stone is suddenly solidified as it nears the earth. High in the atmosphere the meteoric particle is travelling fast enough to maintain the continued melting and vaporization of the surface. But as it comes lower the atmospheric resistance gradually slows it up, so that eventually the melted surface hardens and the meteorite falls through the last few miles as a dark object moving only a few hundred feet per second. The crust on the Bruderheim stones is a dull black. Since most of the stones fell on soft snow the crust has not been broken in the majority of cases. The five largest pieces weigh between fifty and seventy pounds each, and these were

all found at the eastern end of the fall area. This concentration of the heaviest stones towards one side of the region over which the fragments are scattered is a common feature of such falls and indicates the general direction from which the original mass approached the earth. The heavier masses are less affected by the resistance of the atmosphere and so carry on further before dropping to earth. Since the large stones of the Bruderheim were recovered to the east of most of the small pieces, it is an indication that the original meteoritic body was travelling from the west to the east. More exact details of the air path can be determined from an analysis of the visual observations of the brilliant fireball associated with this fall.

In broad general terms meteorites can be divided into two great classes, the irons and the stones. The former consist almost entirely of a nickel-iron alloy, while the latter are primarily of a stony character. However, most of the stone meteorites contain nickel-iron inclusions in significant amounts. The number of stone meteorites that fall to the earth each year is much greater than the number of irons. But the irons can be recognized as unusual objects more easily than the stones. Hence a greater percentage of the irons that fall are recovered, and a museum collection of meteorites may contain almost as many irons as stones.

When an iron meteorite is sliced and the flat surface polished and then etched with nitric acid, the crystal structure of the metal alloy can be seen. This often consists of parallel bands or lines in two or three set directions. They are called Widmanstatten figures after their discoverer. These figures tell us something about the history of iron meteorites, as a crystal structure of this type is formed if the metal is cooled very slowly under conditions of tremendous pressure.

Such conditions are found deep beneath the surface of a planet or satellite. It is obvious that the meteoritic masses which fall to earth must have once formed part of a much larger body. In other words they are fragments, possibly of some disintegrated planet or planets. Measurement of the radio-active elements in meteorites places them in the same age group as the oldest rocks on the earth, that is between four and five billion years old. Recently it has been possible to make some

estimate of the time that has elapsed since planetary disintegrations scattered fragments through the solar system in the form of meteorites. Space is full of high-energy cosmic rays, and when these strike a solid object they cause certain atomic transformations near the surface of the object. The longer the exposure to the cosmic rays the more atoms affected. Thus, by making an analysis of the atoms near the surface of a meteorite and by comparing these with the atoms near its centre, it is possible to estimate how long the meteorite has been exposed to the cosmic rays of space. Such studies suggest that within the last 1,000 million years or so medium sized or small planets broke up into meteorites on several occasions. Most iron meteorites seem to have existed as fragments for hundreds of millions of years, while some of the stones show evidence of having been broken up during the last 100 million years.

Many of the stony meteorites have a composite structure where small broken fragments of stone are embedded in a solid material of a different composition. These give evidence of a rather complicated history, and leave man with yet one more natural puzzle to solve.

Meteorites as a class are completely lacking in the sedimentary type of material, such as the sandstones and limestones common on the surface of the earth. Nor has well-authenticated evidence yet been found in meteorites suggesting life forms that might have existed on these disintegrated planets. This is not too surprising, as biologic life is not likely to develop in the absence of an atmosphere. Bodies like the moon do not have enough mass to hold an atmosphere, and it seems likely that the hypothetical meteorite-forming planets had no atmospheres. Their orbits probably were further from the sun than the planet Mars, and the temperature range in this zone is not conducive to the development of life. It is too soon yet to assess the reliability of some investigations reported in 1961 that molecules of organic origin have been found in meteorites.

A small meteorite, weighing from a few pounds up to several hundred pounds, is so slowed down by the resistance of the air that when it falls it only penetrates a few feet into the ground. A bit of earth may be splashed around but there is no major disturbance.

It is an entirely different story when the total mass of the meteorite is measured in thousands of tons. Such objects are very rare, but when they do arrive they reach the earth with speeds that are not far below the original velocity with which they entered the atmosphere. The energy of even 300 tons moving at fifteen miles per second is equivalent to an atomic bomb of the type dropped on Hiroshima. When a still heavier meteorite strikes the earth the results are catastrophic.

At 10.38 in the morning on February 12, 1947, a very brilliant fireball leaving a great swirling smoke train passed from north to south over the Far Eastern Region of the U.S.S.R. The path of this object ended in a mountainous area north of Vladivostok, part of the Sikhote-Alin range. Scientists of the Soviet Union were able to investigate this event very shortly after it took place. On the wooded hillsides they found over 100 craters ranging in size from the largest over ninety feet in diameter, down to small ones a few feet across. Buried in the earth and on the surface of the ground were large and small pieces of nickel-iron, broken fragments of the body which probably weighed several hundred tons in its original form. Over thirty tons of specimens were collected.

When I visited Moscow in 1958 I met Dr. Krinov, who has taken a major part in the investigation of the Sikhote-Alin fall. I had the pleasure of spending a day with him in the Mineralogical Museum of the University of Moscow. Here the material collected from the Sikhote-Alin craters is on display. The largest iron meteorite recovered is over four feet across and weighs two tons. It has the shape of a flat cone and lines and ridges radiate from the vertex, marking where the melted surface was blown back by air pressure.

This is the first case on record of the fall of a shower of iron fragments, as all previous meteorite showers had been of stone meteorites. The Sikhote-Alin irons were found distributed over an area 3,500 feet long by 1,500 feet wide. The scientific teams collected very complete information on the effect of the falling fragments on trees and soil. Study of this data made it possible to estimate the direction and angle of fall, as well as the force with which each piece struck. From this the approximate velocity of the meteorites could be calculated and this was

found to be about 1,800 feet per second, inclined twenty-seven degrees away from the vertical. When the mass first encountered the upper atmosphere it was moving at a speed of nine miles per second.

A still more spectacular event occurred at 7.17 on the morning of June 30, 1908, when a great ball of fire that outshone the sun passed across the sky and an earth-shaking explosion occurred in the Tunguska river area north of Lake Baikal, U.S.S.R. Eyewitnesses were few as the region is a frozen wilderness far from populated centres, but stories have been pieced together from interviews with the peasants and the nomadic groups that inhabit the area. Apparently when the fireball struck the earth a huge column of flame and smoke shot high into the sky, while thirty-five miles away a farmer sitting on his porch was blown several yards off his chair and knocked out. Detonations were heard as far as 900 miles away. The air blast blew the forest trees flat out to a maximum distance of forty-five miles, and nineteen years later, when the first scientific expedition reached the spot, the dead tree trunks still lay flat on the ground, all pointing out from the explosion centre and remaining as mute evidence of one of nature's most awe-inspiring performances. If such a fall happened by chance to strike near one of earth's large cities, the loss of life would be tremendous. As it was, the dust, scattered into the atmosphere along the path of this object, spread over Europe and Asia and produced luminous twilights and some of the most beautiful sunsets that had ever been seen. The absence of a large permanent crater at the site of the Tunguska fall has been explained on the basis of the region being one of muskeg and permafrost. However, there remain a number of puzzling features in regard to this event. For example, only very minute amounts of meteoritic material have been recovered, and it is evident that much remains to be done in a study of this phenomenon.

Up to the present, I have been dealing with meteorites that have fallen within the last few hundred years. But the earth's face bears the scars of a much more massive bombardment from space that took place long before the beginnings of recorded history. Probably the best known example is the large meteorite crater near Winslow, Arizona. This is called the

Barringer crater, named after the man who in 1909 first suggested its true origin and stoutly defended his hypothesis in the face of general opposition from many scientists. The Barringer crater is a remarkable object, and it has to be seen to be fully appreciated. No picture does it justice. Three-quarters of a mile across and 600 feet deep it looks from the air like a giant pock-mark on the flat Arizona plain. If you stand on the rim you see a vista of precipitous and jagged inner slopes with red and white rock lying jumbled together as it was left by the force of the explosion which took place more than 20,000 years ago. Great boulders twenty feet or more across lie around the rim of the crater, and looking across it to the other side people appear like small dots on the horizon. Large and small pieces of this meteorite have been picked up in great numbers over a circular area out to a distance of six miles from the crater centre. The largest of these iron fragments weighs over 1,400 lb.

Various estimates of the mass of the celestial object that formed the Barringer crater have been made, but no exact figure can yet be given. The energy required to move the rock out of a hole of this size is equivalent to several hundred atomic bombs. If the meteoric mass struck the earth's surface at a speed of twelve miles per second, it must have weighed in the neighbourhood of a quarter of a million tons. A piece of nickel-iron of this weight would have an original diameter just over sixty feet but it is likely that most of it would be broken up into small pieces by the force of the impact. Systematic sampling of the soil for some miles around the crater has resulted in the recovery of large quantities of nickel-iron dust particles. It has been estimated that well over 10,000 tons of this powdered residue from the meteorite lies scattered over the region. Some of it is in the form of tiny metal spheres. These are the solidified droplets of fused nickel-iron produced in the fiery maelstrom that occurred at the crater's birth.

A small museum has been built on the rim of the Barringer crater. Here you can enjoy the view from an observation gallery, or if you are feeling energetic, make the trip to the bottom and back. If you happen to be driving along Highway 66 through northern Arizona I suggest that you stop for an

hour to visit this crater. It is one of the most unique natural features you can see on the earth's surface.

Meteor craters, as single objects or in groups, are now recognized in Texas, Central and Western Australia, Estonia, Arabia, and at a number of other locations. Most of these craters are in dry, arid regions of the earth where surface features are not altered by the growth of vegetation or by erosion resulting from heavy rainfall. It is certain that many more such objects must have been formed on earth, and later eroded by wind and weather. A still greater number of the big meteorites must have fallen in the sea, leaving no permanent signature.

But does the earth's surface bear any evidence of still more ancient scars? It would seem likely that they exist, since all theories of the origin of the solar system suggest more scattered material among the planets hundreds of millions of years ago. Such a condition would naturally lead to a greater probability of collisions between the earth and objects of considerable mass.

One should look for evidence of these very ancient craters in the oldest rock of the earth's surface. Canada happens to have the largest exposed area of this type of rock of any country in the world, so it is not surprising to find there the largest meteor craters of all. The Dominion Observatory in Ottawa has spearheaded a program for the discovery and investigation of these objects, following the initial work of Dr. V. B. Meen of the University of Toronto in his study of the large two-mile crater in the north of the Ungava peninsula.

Extensive investigations have already been made near Kingston at the Holleford crater, 1½ mile in diameter; at the Brent crater, two miles in diameter, located on the north boundary of Algonquin Park; and at the still larger eight-mile-wide Deep Bay crater in north Saskatchewan. Other similar objects are now claiming the attention of Canadian scientists, and it seems that we are only at the beginning of the recognition of such features on the surface of our planet *(Fig. 11)*.

The discovery of these craters has been the product of aerial photography. Most of the Canadian meteor craters were formed hundreds of millions of years ago and are now filled with the sandstones and the limestones deposited by the seas of past

ages. The original contour has disappeared and in some cases people have lived right at the crater for years without knowing of its existence. However, thanks to high-altitude aerial photography, the circular outline can now be detected. The meteorites which produced these Canadian craters probably ranged in weight up to 100 million tons, and in size up to chunks of solid matter 1,000 feet across. The impact that produced Deep Bay in Saskatchewan must have had the energy of several hundred hydrogen bombs.

In this study of meteorite scars on the earth it is natural to look at the pock-marked surface of our own moon, and to speculate upon the possible connection between the lunar craters and the similar features found here. The two groups of craters form a continuous sequence from the small to the large, and it seems likely that most of the large craters on the moon were formed by meteoritic bombardment. Since there has been no air or water on our satellite for billions of years, the surface features have remained essentially unchanged for a long period.

This brings us to the end of our review of earth's visitors. We have moved from the thousands of tons of space dust dropped each day, up through the visible meteors which are mostly cometary fragments, to the fireballs and meteorites,

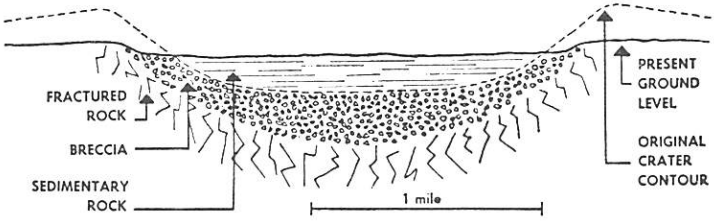


FIG. 11. A vertical section through a typical ancient meteorite crater of the type recently discovered and studied in Canada, adapted from a drawing by C. S. Beals.

broken pieces of little planets. The biggest members of this last group, monster meteorites of past ages, have left great marks that remain indelible after hundreds of millions of years. The study of our visitors from space has written an important chapter in the story of the solar system.

WHAT IS THE SUN?

4

EVER since the dawn of intelligence in the human race, man has intuitively recognized his debt to the sun as the source of light and warmth on the earth. The sun was deified repeatedly in primitive religion. Nearly 4,000 years ago great stone circles in England were laid out in relation to the positions of the sun. The Egyptians had at least three sun gods, Horus, Amon and Ra. The sun was the god Shamask of the ancient Babylonians. Helios of the Greeks, and Sol of the Romans. And in the New World the Incas built their great temples to the sun.

The sun is the centre of our system of planetary worlds. It maintains a gravitational control over the entire solar system consisting of planets, satellites, asteroids, comets, and the fragmentary material or dust which lies between. It also controls the physical conditions on these worlds, and determines all activity which takes place on their surfaces. This is one aspect of the sun.

But, as we discuss the sun's nature and its relation to our existence, I want you to think of another aspect. The sun is the closest star to us, and the only one we can study in great detail. It also happens to be a very average type of star so that, as we look at various features of the sun, we should take it as typical of the billions of stars that appear as mere points of light in even the largest telescope. When describing other stars it is often convenient to list their physical properties in terms of the corresponding values for the sun, taken as a standard.

What, then, is the sun? Briefly, in simple terms, it is an

immense sphere of very hot gas. But now, having said this, I must add a few words of explanation. The gas inside the sun is subjected to such great pressures that it is highly compressed, and may have a density greater than most solid objects. The temperature is so high that all the normally solid substances, like iron and silicon, are in the form of gas. And finally, the heat of the sun is not a result of a chemical combustion, like most fires on earth, but is the product of atom burning, in other words nuclear fusion. This is the same process, going on continuously at the centre of the sun, that man sets off explosively in the hydrogen bomb. But even the H-bomb is a small thing when compared with the sun. If the entire earth were covered by a layer of ice one mile deep, and all the energy of the sun were used to melt it, the ice would be gone in less than seven seconds; and this tremendous energy production has been going on for at least five billion years.

We look at the sun across a distance of ninety-three million miles. Its diameter is 865,000 miles, just 109 times the diameter of the earth. Although the sun is a sphere of gas, semi-permanent features are seen on its surface, the best known of these being the sunspots. By watching the sunspots we conclude that the sun turns on its axis counter-clockwise as seen from the north. For some reason that is still a mystery, different parts of the sun rotate with different periods. The equatorial regions make one rotation in twenty-five days, but the polar regions take close to thirty days. As seen from the earth, which is itself moving round the sun in the same direction as the sun's rotation, a sunspot of long duration will cross the solar disk at intervals of twenty-seven to twenty-nine days.

The temperature of the solar surface can be estimated from the brightness and the colour of sunlight, since the hotter a light source is, the brighter it will shine and the bluer will be its colour. The sun is a yellow star and its surface temperature is very close to ten thousand degrees Fahrenheit. This corresponds to 5,800° on the Kelvin or absolute temperature scale, which is more commonly used in scientific work *(see Appendix B)*. From now on I will be giving temperatures in the Kelvin scale.

We cannot observe the inside of the sun directly, but we can

find out a lot about it by the use of certain methods of reasoning first developed by Sir Arthur Eddington. We start with the hot gaseous surface which we *can* see and which has a temperature about 5,800° Kelvin. The layer in the sun directly below this must be at a higher pressure since it supports the weight of the gas above. It must also be at a higher temperature, since heat is flowing out through the surface layer, from the interior. If it were cooler inside, the heat would flow in. Following this general type of argument we conclude that, as we go down into the sun, we encounter steadily increasing temperatures, pressures, and densities. Solids and liquids could not exist under these conditions, so the material inside the sun must be a gas. We have seen that energy, in the form of light and heat, is continually streaming out from the centre of the sun to its surface. Strong light exerts a force called radiation pressure and this, along with normal gas pressure, supports the weight of the outer layers of the sun.

Now, taking the size and mass of the sun, together with the temperature found at the surface, and using the known properties of a gas, we can calculate by a trial and error procedure that the centre of the sun must be at a temperature not far from fifteen million degrees Kelvin. The corresponding central density may be as high as 100 times that of water.

To understand what is going on inside the sun we must stop for a moment and take a look at the properties of atoms. Matter in our physical world consists of the atoms of some ninety-two different elements, from hydrogen, the lightest and simplest, up to uranium, the heaviest and most complex. Still heavier unstable atoms have been made artificially in the physics laboratory. Atoms are tiny things; 100 million placed side by side would form a line less than an inch long. But practically all the weight of an atom is concentrated at its centre in something very much smaller still—the nucleus. Even the nucleus of an atom has its component parts and can be broken up and altered. Among other things in the nucleus we find protons which are small particles that carry positive charges of electricity. The simplest nucleus is that of the hydrogen atom, consisting of just one proton. Others are heavier and contain more protons. In the outer parts of atoms we have electrons, very

light particles that carry negative charges, and these negative charges just balance the positive charges of the protons, leaving the atom as a whole without a charge. If an atom is hit hard enough some of its electrons can be knocked off it, and it is said to be ionized. The significance of ionization is that it leaves the atoms with positive electrical charges and produces a cloud of negative charges in the form of electrons.

At the very high temperatures inside the sun the atoms are moving very fast and practically all have lost electrons and are ionized. But more than this, the nuclei themselves jostle each other so hard that their protons and other component parts are interchanged and rearranged. Two protons can become fused together as a unit, then these can pick up a third and then a fourth proton, making a compact particle of four parts. This is the nucleus of a helium atom, and it has been built out of the nuclei of four hydrogen atoms. The process is called atomic fusion and results in the conversion of a certain fraction of the mass of the atoms into energy. The particular type of fusion I have described is known as the proton-proton cycle, and it is probably the one which is of major importance in the sun. You could say that the sun burns hydrogen to produce energy, and leaves helium as the ashes.

What about the composition of the sun? I think most people realize that a spectroscope analyzes light, and we have noted earlier that the spectroscope makes it possible to identify the elements in a distant source. This ability to determine the composition of objects at a distance makes the spectroscope a most powerful instrument for the astronomer to use.

Let me describe the beginning of spectroscopic analysis, an experiment that was performed in 1814, nearly 150 years ago. Joseph Fraunhofer, a young German optician, made a narrow vertical slit in the shutter of a darkened room. He then let sunlight from this fall on a prism and observed it with a small telescope. This experiment can be repeated by any student in physics. Fraunhofer noted at once that the band of colour, ranging from violet at one end to red at the other, was crossed by a large number of fine dark lines, and that these always appeared at exactly the same places and with the same arrangement. However, when he examined other light sources such as

lamps, these dark lines were missing. He concluded correctly that these lines were a special property of sunlight, and were not produced by his instruments. He mapped over 600 of them and they are now known as the Fraunhofer lines. Modern tables of the solar spectrum list more than 25,000 of these lines.

White light is made up of all the colours of light mixed together. The band of colour produced by a prism, or by the sun shining through the corner of a glass ornament, is called a spectrum. Here all the component wave-lengths in a beam of light are arranged in order, from the short wave-lengths in the violet to the long wave-lengths in the red. The dark Fraunhofer lines in the sun's spectrum indicate certain missing wave-lengths. The physical explanation of these came many years later when it was discovered that certain specific wave-lengths were always associated with the atoms of a given element. A hot gas of low density composed of any element shines with a particular set of hues or colours. For example sodium has a very characteristic yellow-orange line, which actually consists of a pair of lines very close together. But when the sodium light is seen against the background of a brighter source, as happens in the sun, these lines become dark against a bright background. In either case, whether bright or dark, the pattern of spectrum lines is a sure identification of the atoms in the source.

We now return to the sun and its composition. It is not difficult to make a list of the elements that have been identified in the solar atmosphere. Over sixty different elements are represented among the Fraunhofer lines observed. It is a much tougher problem to determine the relative proportions of these elements in the atmosphere, and still more difficult to decide about the composition of the solar interior. Everyone agrees that the two lightest elements, hydrogen and helium, make up most of the mass, both inside the sun and on its surface. On the surface, hydrogen and helium account for nearly ninety-nine per cent of the mass. One and a quarter per cent is divided among all the rest of the elements. Of these, carbon, nitrogen, and oxygen, are the most important, followed by magnesium, silicon, sulphur, and iron. In the interior it is believed that these heavier elements may be in slightly greater proportion compared to the hydrogen and helium. It is interesting to note that the name

helium, from the Greek ἥλιος, commemorates the fact that this element was first identified in the sun, and this was twenty-seven years before it was produced in laboratories on earth.

Up to the present we have been looking at the sun purely as a static object, a great sphere of gas that exists at the centre of our solar system. But the sun has striking dynamical characteristics, some of which are only now being fully appreciated. Along with the ultra-violet, visible, infra-red, and radio waves, the sun fires into the space around it streams of small atomic particles. These have been likened to a great solar wind, forever blowing outward from our system's centre, and interacting with anything that lies in its path. A second characteristic we find in the sun is that of a deep-seated variability, a long-term periodic change. One evidence of this is the variation in the numbers of sunspots in a period just over eleven years.

I have already pointed out that the energy of the sun is produced in its very hot central core. This radiant energy moves out to the sun's surface, assisted in the outer layers by a turbulent boiling motion of the gas. Now let us pause for a moment at this solar surface. When you look at the sun through a piece of dark glass it seems to have a perfectly smooth, solid-looking edge, but this appearance is misleading. The properties of the hot gas at the edge of the sun are such that it becomes opaque to light over a certain depth, much like the border we see to some fog bank. The opaque edge is not quite so sharp as it seems, but at the distance of the sun even a thousand miles will look pretty small.

A close-up view of the solar surface reveals it as a seething mass of great flame-like plumes of hydrogen, helium, calcium, and other atoms. These are called prominences and they dwarf the earth with their size, as they may extend upward for 100,000 miles or more. They show great variety in shape and motion, and often conform to strong magnetic fields found locally on the sun, particularly near sunspots. The sunspots were recognized as a regular feature of the solar surface shortly after the telescope came into use. They are cooler than the surrounding areas but appear black only in contrast to the rest of the sun. Actually the darkest part of a sunspot is as bright as the light source in a white photo-flashbulb.

The sunspots are one of the most easily observed evidences of the basic variability in the sun which I mentioned earlier. For about five years the average number of spots on the sun's disk increases, then for the next six years it decreases, giving a period which averages just over eleven years. When we measure the magnetic fields near the spots we find that for eleven years spots in certain locations have a north magnetic polarity, then, for the next eleven years, they have a south polarity, giving a reversal of the local magnetic fields every eleven years. Hence, the full period on the sun is actually 22½ years, with two sunspot maxima in each full period. The current view of the nature of a sunspot is that, as a result of a strong magnetic field, it is an area of relative calm in turbulent surroundings. Lack of convection to bring heat up from the interior keeps the spot some 2,000° cooler than the prevailing temperature of the surrounding surface. To compensate for this the regions around large sunspots are often found to be abnormally active, and covered with bright clouds of hot gases from below.

Individual spots are transitory phenomena on the sun's surface and various ingenious suggestions have been made to explain their occurrence, but none of these is entirely satisfactory. And a bigger puzzle still—why the 22½ year cycle? No one has even come near a good solution to this.

In this connection, I can give you some more observational evidence to think about. The visible and infra-red radiation from the sun varies hardly at all—less than one per cent—and any small change there may be shows little connection with the sunspot cycle. But it is a different story for certain radio wavelengths. Here the strength of the radio emission follows the sunspot numbers very closely. The most extended series of radio observations of the sun has been made at the National Research Council by A. E. Covington, using a wave-length near eleven centimetres. In 1947, near sunspot maximum, the radio energy was 260 on the scale which he used. This dropped to 70 in 1954 at sunspot minimum, but rose again to 280 in 1958 during one of the highest sunspot maxima ever recorded. From a study of the earth's upper atmosphere we conclude that the ultra-violet radiation from the sun also varies considerably with the sunspot period.

One of the most beautiful sights in the sky is the extended outer atmosphere of the sun known as the corona. Unfortunately this is normally invisible as its faint light is hidden by the glare of sunlight scattered by our atmosphere. Only when the moon comes between earth and sun, at the time of a total solar eclipse, do we see the corona in all its glory. It then shines with a pearly white glow, the total luminosity being roughly equivalent to that of the full moon. Long curved streamers extend out from the edge of the sun, sometimes for distances exceeding five solar diameters, and many of the coronal features give evidence of conforming with the general magnetic field of the sun. The shape of the corona changes in a striking way along with the frequency of sunspots. At sunspot maximum we see a fairly uniform globular distribution of coronal rays, but at the time of sunspot minimum the corona usually extends in very long streamers from the sun's equatorial regions, while at each pole we see a symmetrical pattern of short curved rays that look like the magnetic lines of force around a bar magnet (*Fig. 12*). Here we have evidence that the sun's general magnetic field plays an important role in connection with the 22½ year period.

The light of the corona is complex, and for many years could not be explained satisfactorily. The appearance of certain particular wave-lengths of light as bright emissions led to the serious suggestion that an unknown element might be shining in the corona. But it turned out that the missing clue depended on a question of temperature. The centre of the sun is at millions of degrees, and the temperature falls steadily to less than 6,000° at the surface so it was natural to suppose that the sun's outer atmosphere was at a still lower value. This is where the surprise came in. The atoms in the corona behave as if they were at a temperature of a million degrees. The mysterious, unrecognizable light turned out to be from the well-known atoms of iron, nickel, calcium, and argon, masquerading as strangers with anywhere from nine to fifteen of their electrons, or negative charges, stripped off. We can thank the young Swedish physicist Edlen for the solution to this astronomical puzzle. The high coronal temperature which produces these disheveled atoms is confirmed by several independent lines of

evidence. For example this part of the solar atmosphere is the source of a large portion of the radio waves from the sun, and the strength of these also corresponds to a temperature of at least one million degrees. But the solution of one puzzle merely leaves us with another. So far no one has fully explained what keeps the corona in this very unexpected condition.

As we look at the turbulent solar surface and watch the ever-changing pattern of the flaming prominences, we see motions in all directions, up, down, along magnetic lines of force. Every now and again, over a disturbed area we see an eruptive prominence, a mass of gas that seems to be blown off the surface by something like an explosion. One of the most spectacular of these was a prominence on June 4, 1946, a loop of hydrogen gas which moved out at a speed that exceeded 100 miles a second, and eventually became almost as big as the sun itself. Here is evidence before our eyes of clouds of atoms projected out into the space around the sun. We know also that negatively charged electrons exist in the corona in great numbers and that their density falls off with increasing distance from the sun. A third component of the outer solar atmosphere consists of tiny solid particles, space dust, which I have described earlier.

The corona and its associated features have no sharp outer boundary, and the very tenuous portions of the solar atmosphere can be considered as extending out a long way into space and actually merging into the outer atmosphere of the earth. For example in every cubic inch of space at the earth's distance from the sun there are probably more than 1,000 electrons and over 1,000 protons. Visual evidence of the extreme extension of the sun's atmosphere is found in the zodiacal light, a faint elliptical luminosity that lies near the average plane of the planetary orbits, and which can be seen at certain times of the year in the west after sunset or in the east before sunrise. Like a very faint super-corona it can be detected as much as ninety degrees from the sun. Most of the zodiacal light seems to originate in sunlight scattered by the interplanetary dust.

Every now and again, usually near a large sunspot, an extremely bright outburst of gas occurs quite unexpectedly. This is called a solar flare and is normally a short-lived phenomenon with a duration measured in minutes. Only a few of the very

brightest last more than an hour. A flare is not generally evident unless we view the sun with a special filter which separates out a particular wave-length of light that corresponds to a gas common on the sun. A suitable wave-length is a deep red called the hydrogen alpha line, and observations of prominences and flares are commonly made by viewing the sun in this one colour of red.

When a large flare takes place near the centre of the sun's hemisphere that is facing us, it touches off a series of events

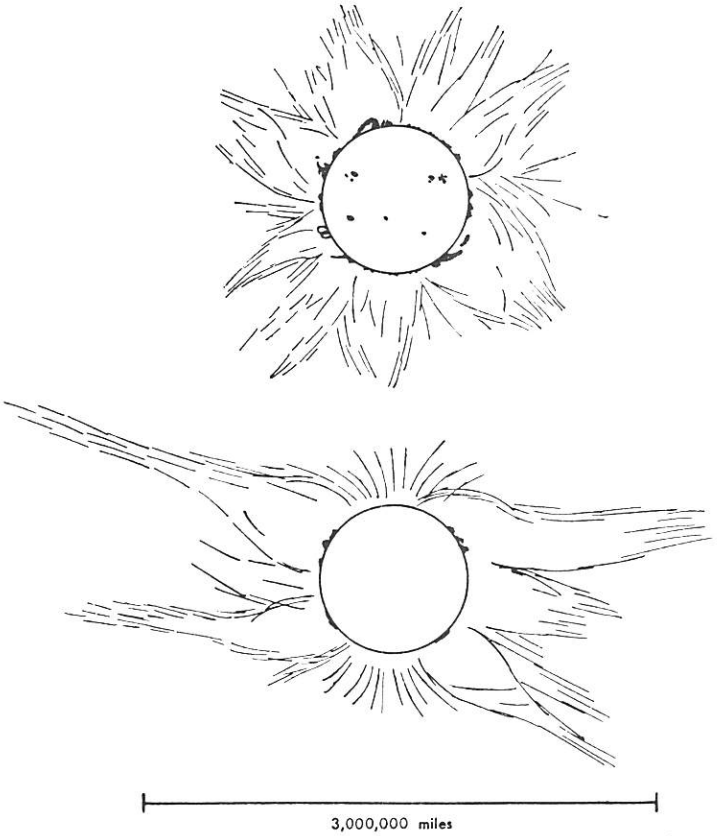


FIG. 12. Typical forms of the sun's corona near sunspot maximum (above) and near sunspot minimum (below).

at the earth which clearly demonstrates the close physical relation between the sun and our planet.

First of all the flare emits a strong burst of ultra-violet light which travels from sun to earth in eight minutes. When this light arrives it ionizes the upper air, that is it separates negative electrons from the molecules and atoms of our atmosphere, thus creating a new layer of charged particles called the ionosphere, at a lower height than usual. The effect on radio transmissions across the daylight hemisphere of the earth is immediate and disastrous. Signals become very weak, and there may be a complete fade-out of radio communication for the duration of the flare. Bursts of noise on the radio wavelengths are also emitted by the flare and arrive simultaneously with the ultra-violet light.

Then about a day later, streams of charged particles surround the earth and touch off the sudden commencement of a severe magnetic storm accompanied by strong earth currents and, in the polar regions, by auroral displays. These charged particles have travelled from the sun at a speed which averages close to 1,000 miles a second. As they reach the neighbourhood of the earth they are channelled by the earth's magnetic field into zones around the geomagnetic poles in the north and south. In these zones auroral displays, often called the northern lights in our hemisphere, are seen with the greatest frequency. The northern auroral zone crosses Canada through Labrador, across Hudson Bay not far from Churchill, Manitoba, and then on past Yellowknife into Alaska and the Arctic Ocean.

One of the most striking solar-flare events in recent years occurred early in 1958. On the night of February 10th a brilliant red aurora was seen over all of Canada and the United States, and even down into Mexico. On that Monday evening it was impossible to get radio reception in parts of the United States and Canada owing to the very strong magnetic storm that commenced about 8:30 p.m. E.S.T.

We have seen that both the general magnetic field of the sun and the localized magnetic fields near sunspots have a very important bearing on the nature and degree of solar activity. In the same way the earth's magnetic field has a primary role in regulating and controlling our direct contact with this solar

activity. However, it was only in 1958, during the International Geophysical Year, that the American earth satellites first mapped out two large doughnut-shaped belts of high energy particles that surround the earth *(Fig. 13)*. These conform to the lines of force in the earth's magnetic field and have been named the Van Allen belts, after the leader of the scientific team that discovered them. The outer belt, roughly 30,000 miles across, probably traps electrons coming from the sun and possibly acts as a reservoir for these particles which may later heat the atmosphere or produce auroras. The inner belt, with less than half the diameter of the outer, contains both electrons and protons. These may be secondary products of very high energy cosmic rays from space. And far below these belts, at heights from 50 to 250 miles, we have the earth's ionosphere, the zone

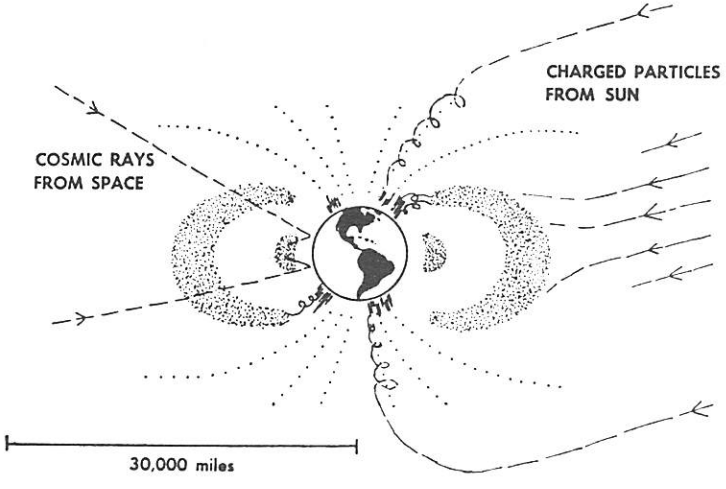


FIG. 13. Charged particles from the sun, and other energetic radiations from space, form two doughnut-shaped belts around the magnetic equator of the earth. Aurorae appear mainly in two zones about the north and south geomagnetic poles, particularly during disturbed conditions in the earth's magnetic field.

of low-energy charged particles, which acts like a curved mirror, reflecting radio waves and making possible long distance radio communications.

This whole complex of solar and terrestrial magnetic fields, charged particles of various energies, solar radiation, interplanetary dust, and cosmic rays, forms a unit that pulses with the basic period of the sun. I have mentioned the bright solar flares and the great magnetic storms associated with them. But there are smaller magnetic disturbances that are not associated with flares but which show a tendency to recur at twenty-seven-day intervals, a rotation period of the sun. These must owe their origin to disturbed areas on the sun not yet identified with certainty.

There is no doubt that terrestrial features, such as the strength of magnetic disturbances and the frequency of aurora, bear a close one-to-one relation to the variation in the number of sunspots and the strength of the radio waves coming from the sun. But when we come to other more indirectly related statistics such as annual rainfall or the numbers of fur-bearing animals, we must move with caution before relating these directly to the sunspots. In most cases local weather factors, or independent biological cycles, complicate the situation and make a definitive analysis almost impossible.

Concerning one aspect of the sun's influence on the earth there is not much doubt. Except for radio-activity and certain other forms of atomic energy, all sources of power come directly or indirectly from the sun, and it is the energy from the sun which maintains life on the earth.

BIG STARS AND LITTLE STARS

5

IN this chapter I am going to deal with stars, stars of various shapes, sizes, and colours. The subject is a basic one, since a large portion of the matter in our universe exists in the form of stars.

A casual glance at the stars on a clear night may leave you with the impression that one star is very much like another and, as the Dormouse put it in *Alice in Wonderland*, they are 'much of a muchness'. But a second and more careful look tells a different story. In the first place the stars have a large range in apparent brightness. The brightest star in the sky is over 1,000 times as luminous as the faintest we can see with the naked eye. Then, one can hardly fail to detect colour differences among the brighter stars. For example in the summer sky we have a bright, blue-white star, Vega, high overhead in the constellation representing the Lyre; while in the south we see Antares, glowing a deep red in the constellation of the Scorpion. In this recognition of different brightnesses and different colours among the stars we have two of the most important and fundamental classifications that astronomers use in studying groups of stars and their life histories.

When the astronomer speaks of the magnitude of a star he does not mean size. He is using a special number scale to describe star brightness. This scale originated nearly 2,000 years ago with the early star catalogues. Stars in the brightest group were said to be of the first magnitude, those somewhat fainter second magnitude, and so on down to the faintest that

could be seen with the naked eye, called sixth magnitude. When the telescope was invented still fainter stars were visible, and the magnitude system was simply extended to higher numbers *(see Appendix B)*. A good pair of binoculars will show stars down to the tenth magnitude, and with the 200-inch telescope on Mt. Palomar stars of the twentieth magnitude can be seen. The bigger numbers refer to the fainter stars and five steps on the magnitude scale correspond to a brightness ratio of 100. A first-magnitude star has the same brightness as a standard candle placed at a distance of seven-tenths of a mile.

The magnitude of a star tells us how bright it appears in the sky. But the distance of the star will affect this apparent brightness and to find some measure of the intrinsic or absolute brightness we must make a correction for distance. Star distances are so great that a unit such as a mile is too small to use. A convenient unit of length is the light-year, that is the distance that light travels in one year. Light moves at a speed of 186,000 miles a second, and if you multiply this by the number of seconds in a year you find that a light year equals nearly six million million miles, that is six followed by twelve noughts. The closest star apart from our sun, is just over four light-years away. A space probe from earth, travelling 96,000 miles per hour, would take 30,000 years to reach it.

The distances of the nearby stars are found by simple trigonometry. You remember the school-book problem of finding the distance across an impassable river. By observing a tree on the far bank from the two ends of a measured baseline, it is possible to solve the triangle thus formed, and find the width of the river. As the earth moves around the sun in its orbit, the diameter of this orbit, that is twice ninety-three million miles, gives us a long baseline. Due to the earth's motion, the closer stars shift their positions against the more distant objects. By observing this displacement of a star on the sky background we have the angle at the apex of a long narrow triangle that has the earth's orbit as a base. Solving the triangle gives us the distance of the star *(see Appendix B)*. This method becomes too inaccurate to be of much use for stars further away than 100 light-years, but within this limit it is quite helpful and for about 1,000 stars closest to the solar system we have fairly reliable

distances found by trigonometry. Using this group of stars as a primary standard we can determine the distances of other objects in various ways that will be discussed later.

We have already discussed the details of the solar surface and the structure of the solar atmosphere, but unfortunately the sun is the only star we can study directly like this. All other stars are so far away that even the 200-inch telescope will not show detail on their disks. Yet, by indirect methods, we have found out a great deal about a great many stars. The investigation of the physical structure of the stars has posed a challenge to man's ingenuity, and it is here that the power of analytical and deductive reasoning has been demonstrated in a striking manner.

Most stars have certain physical properties in common. The material of which they are composed is a gas, but it may have a density greater than most solid objects, and may consist of many of the heavy atoms like iron or silicon. The pressure and density of this gas increase as we move from the surface of a star towards its centre. The temperature at the surface is high, but it is very much higher in the central portion where most of the energy is produced. This energy results from the fusing together of light atoms to make heavy ones, nuclear reactions of various kinds that are only possible at temperatures measured in millions of degrees. The energy produced flows out from the centre of a star to its surface, where it appears as light and heat, and it is by analyzing this radiation which escapes into space that we learn about the physical nature of the stars.

As already mentioned the two basic classifications of stars are brightness and colour. It has been found that, in general, the stars which have the greatest absolute brightness are the most massive objects. The colour of a star depends primarily on its surface temperature, and we find a range all the way from the blue-white stars at 30,000° down through white, yellow, and orange to red stars, with surface temperatures less than 3,000°. To give you some idea of the great variety we find among the stars when we consider them individually, I have chosen eight particular stars or star systems as examples. We will visit each of these in turn and note some of the things that have been learned about them. It will be found convenient to express

stellar sizes in terms of the sun's diameter—865,000 miles—and stellar masses in terms of the sun's mass—equivalent to 330,000 earths or 2,200,000,000,000,000,000,000,000,000 short tons.

The first star on the list is named Antares, which means the rival of Mars *(Fig. 14)*. I mentioned this earlier as a bright red star in the Scorpion. Antares is a very large star with a diameter roughly 400 times that of the sun. This means that it is big enough to contain the entire inner portion of the solar system with the orbits of Mercury, Venus, Earth, and Mars, as well as some of the asteroids. In spite of its large size Antares has a mass only ten or twenty times the sun's mass, which gives it a density about one-thousandth of our air at sea level. Under these conditions Antares has no sharp boundary, and it is not surprising that we do not have an exact value for its size.

Large and massive stars of high luminosity are termed giants. The total luminosity of Antares is somewhere between 1,000 and 10,000 times that of the sun and it is generally classed as a supergiant. The energy required to maintain this great brightness is produced in the interior of the star, probably by several processes that involve the formation of helium out of hydrogen, and possibly also by the building of helium into still heavier elements. The central temperature of Antares may be as high as 100,000,000°, much higher than the central temperature of our sun.

The second star system we visit is quite a contrast to the first. It is invisible to the naked eye and consists of a faint pair of red stars, magnitudes nine and ten, in the constellation Cepheus, the King. This pair of stars is known as Kruger 60, a name based on a catalogue number *(Fig. 15)*. Kruger 60 is representative of the large numbers of stars in the sky known as double stars or, to use a more technical term, binary stars. It was Sir William Herschel who, over 150 years ago, first showed that most stars which appear double are relatively close to each other in space, and revolve about a common centre of gravity. At least half the stars near the sun are double or multiple systems, so the tendency to double up seems very prevalent. Although I did not mention it earlier, Antares, the first star visited, has a faint companion star near it.

In the case of Kruger 60 the two stars make one complete revolution in just over forty-four years, and their distance apart varies from 500 million miles to over twice this value. Double star orbits are always ellipses; for stars, like planets, move according to Kepler's laws. The period of revolution of two stars depends on their distance apart and their combined mass, and the study of a double-star orbit provides us with a very direct method of finding the masses of stars. For example, we know that the combined mass of the two stars of Kruger 60 is equal to four-tenths that of the sun. Judging from their relative brightness we can estimate the brighter star as one-quarter the sun's mass, and the fainter star as one-seventh the mass of the sun. The latter is one of the least massive stars we have observed. These stars are among our close neighbours in space, being only thirteen light-years away. Their diameters are considerably smaller than the sun's and they are classified as red dwarfs.

The fainter member of the pair forming Kruger 60 has an interesting characteristic which links it to our sun in behaviour.

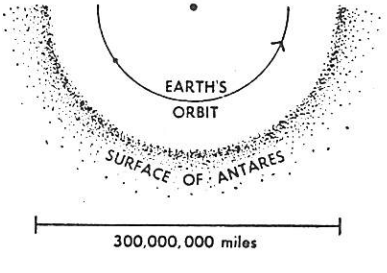


FIG. 14. *Antares*—red super-giant star.

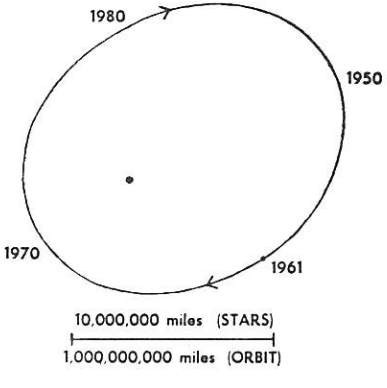


FIG. 15. *Kruger 60*—red dwarf stars.

Every now and again it brightens suddenly for a minute or two as a result of the outrush of a great flare of bright gas, and it is hence called a flare star. The flares produced by our own sun, and described earlier, are probably of the same type but are much less intense.

Star number three on our visiting list has the official catalogue number HD 47129 but it is often referred to as Plaskett's Star, after the late J. S. Plaskett, the Canadian astronomer who first discovered its unique properties from observations made at the Dominion Astrophysical Observatory near Victoria, B.C. *(Fig. 16)*. Plaskett's Star appears as a single point of light in even the largest telescopes and it was only by observing this object with the spectroscope that its interesting features were discovered.

You will recall that the spectroscope is an instrument which analyzes light by separating out the various colours, or wave-lengths, into a band of colour called a spectrum. When Plaskett's Star was observed with the spectroscope it was found that twice every 14½ days all features in the spectrum became double, one component being shifted to the violet, or short wave-lengths, the other to the red, or long wave-lengths. The light had a split personality and gave evidence of coming from two stars.

To understand the physical picture, it helps to think of sound waves instead of light waves. You have all heard the noise of an approaching locomotive whistle or automobile horn, and noted the drop in pitch after the vehicle has passed and is receding from you. This, called the Doppler effect, results from the fact that you receive more waves of sound per second, and hence sound of a higher pitch, from an approaching source than from a receding source. There is a parallel effect in the case of light. An approaching light source produces more waves per second, that is a higher frequency, at the receiver. A higher frequency means a shorter wave-length and a shift to the violet end of the spectrum. Similarly, a receding light source produces a shift to the red end of the spectrum. The amount of the effect is proportional to the velocity of the light source. It is thus possible to find the velocity of a star in the line of sight, and this is called a radial velocity. For over fifty years

Canadian astronomers have specialized in making such measures of stars. As a matter of fact Canada has contributed about one-third of all stellar radial velocities determined.

In the case of Plaskett's Star we have one star approaching while the other is receding, as the two stars revolve about their common centre of gravity. A star like this, whose double character is revealed by the spectroscope, is called a spectroscopic binary. Since we know both the speed of the stars and the period of revolution, we can find the size of the orbit and from this the masses of the two stars.

In the system we are discussing, the two masses are each at least ninety times the sun's mass—possibly more. This makes them the most massive stars known. The stars are both blue-white supergiants, whirling around each other at over 150 miles per second. Each member of the pair is nearly twenty million miles in diameter, but they are closer together than Venus and the sun are in the solar system. The very high surface temperatures of 30,000°, plus the tidal forces of each star on its companion, produce a chaotic and somewhat un-

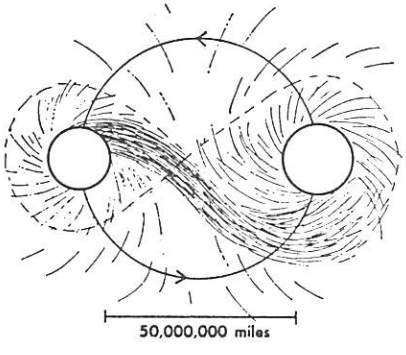


FIG. 16. *HD 47129*—blue-white supergiant stars.

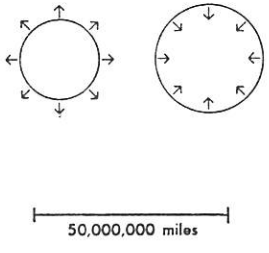


FIG. 17. *Delta Cephei*—pulsating supergiant star.

stable condition. Great streams of helium and hydrogen gas spiral between the stars and envelop them both in an immense cloud which is expanding at a speed of over 400 miles per second. Plaskett's Star shines with a luminosity about 30,000 times that of the sun, but because it is 10,000 light-years away we see it only as a faint star of the sixth magnitude, barely visible to the naked eye.

Plaskett's Star and Kruger 60 are near the two extremes of observed star masses. The most massive star contains only about 1,000 times the quantity of matter found in the least massive. Stars vary much more in brightness, size, and density. But, as Eddington pointed out some time ago, stars are restricted in mass to values that do not differ from the sun's by more than a factor of 100. If a star has too little mass it will not develop the internal conditions necessary for energy production, and so it will not shine. If a star has too large a mass, the energy developed is so great that it will blow the star to pieces.

We now come to star number four, Delta Cephei, a faint star in the constellation Cepheus *(Fig. 17)*. As early as 1784 this star was discovered to vary in brightness by John Goodricke, a young Englishman from York who was a deaf-mute and died at the early age of twenty-two. The change in luminosity is regular and the star reaches maximum brightness at intervals of five days, nine hours. This fading and brightening results from a rhythmic pulsation of the star that may involve a total change in the diameter of as much as twenty or thirty per cent. Delta Cephei is brightest when it is expanding most rapidly. It then fades as it reaches its greatest size and continues to fade as it starts to contract, being faintest when shrinking fastest. There is a regular change in colour and surface temperature along with the change in size. The star is whiter when it is brightest and becomes yellower as it fades. The total change in surface temperature is about 1,500°.

Delta Cephei is a supergiant star which varies from 2,000 times to 5,000 times the sun's brightness. It has given its name to an important class of variable stars called cepheids. The absolute brightness of a cepheid is related very closely to its period of light variation, the longer the period, the brighter the star. Hence, if the period of a cepheid is found, its absolute

brightness, or candle power if you like, is known. Now this information can be used to determine distance.

Let me illustrate. Suppose you have a sixty-watt light-bulb in your living room, located eight feet from your eyes. Looking across the street you see another sixty-watt light on your neighbour's porch. If the light in your living room appears 100 times as bright as the one across the street, then you conclude that the latter is ten times as far away or eighty feet away, since brightness falls off as the square of the distance. Your ability to estimate the distance depended on knowing that your neighbour's light was a sixty-watt bulb. Exactly the same rule can be applied in the case of the cepheids and they provide the astronomer with one of the most powerful methods we have for the determination of distances in the universe. Delta Cephei itself is 1,300 light-years away.

The next star we visit, number five, is Algol known to the Arabs as 'Ras al Ghul', the Demon's Head, and to the Hebrews as 'Rosh ha Satan', Satan's Head *(Fig. 18)*. In the Greek mythology this star marked the terrible, snake-covered head of the Gorgon that Perseus killed. Algol is a second magnitude star in the constellation Perseus. Like Delta Cephei it is a variable star that was studied by young Goodricke in the eighteenth century, but it is fairly certain that the Arabs noted its strange behaviour long before this. Every two days and twenty-one hours this star fades to one-third of normal brightness and then recovers, the entire process taking about ten hours. It is quite easy to observe the fading of Algol with the naked eye as it goes from second magnitude to a little fainter than third magnitude. Like a great eye in the heavens Algol slowly winks, and it may have been this property which induced so many of the ancient observers to associate it with an unpleasant type of head. The Chinese went even further and called it a 'Pile of Corpses'.

Goodricke suggested the correct solution for the light variation of this star, though it was not until many years later that his theory was verified by the spectroscope. Algol is a double star, one component being a bright white star the other a dull red star. Every two days twenty-one hours the dark star passes between the bright star and us, causing an eclipse

of most of the light of the bright star. This type of double star is called an eclipsing binary.

Spectroscopic measures of the radial velocities in this system give us the speeds of the stars in their orbit and, since we know the period, the size of the orbit can be determined without difficulty. The duration of the eclipse compared to the whole period tells us the size of the stars relative to the orbit. By a careful analysis of the way the light varies it is possible to determine the actual surface brightnesses of the two stars, and whether one side is brighter than the other. Stars in such systems are often so close together that they mutually reflect light from each other, which gives each star a bright spot on the side facing its companion. We can find out a lot of very detailed information about any eclipsing binary that can also be observed with the spectroscope. The two stars in the Algol system are thirteen million miles apart, and both have diameters near three million miles, the faint star being the larger. But even the fainter of these stars is brighter than the sun. Algol is just over 100 light-years distant from us. It is of interest to note that there is a third star in this system which moves around the close pair in a period just under two years.

Star number six on our list is the second brightest star in the little constellation of Lyra, the Lyre, and is known as Beta Lyrae *(Fig. 19)*. Since its distance is 1,300 light-years, the light that we see today started on its journey about the time of King Arthur and the Knights of the Round Table. This is another star whose variations in brightness were discovered by John Goodricke in 1784, shortly before his untimely death. Beta Lyrae is an eclipsing binary star; and here we find two stars so close together that their surfaces are practically in contact. Such proximity raises huge tidal forces, and both stars are drawn out into shapes somewhat like two immense eggs lined up end to end. The centres of the stars are about fifty million miles apart, and they move round each other at speeds between 100 and 200 miles per second. It takes them almost thirteen days to make a complete circuit and twice during each revolution—that is every 6½ days—one of the stars hides the light of the other. This period of revolution becomes ten seconds longer each year.

The components of Beta Lyrae have a combined mass thirty to forty times that of the sun. The brighter star is blue-white in colour, the fainter star yellow, and they are classified as supergiants. The great tidal forces not only deform both stars, but cause streams of hot gas to be ejected from them. These streams expand and envelop the whole system in a cloud which probably assumes a spiral form as it moves out. It is likely that this cloud obscures certain features of the stars, and may prevent us from knowing their true luminosities. It is not even certain which of the two stars is the more massive. The system still presents many problems to the astronomer.

Epsilon Aurigae, the seventh star, is near the bright star Capella *(Fig. 20)*. In mythology Capella is known as the she-goat and Epsilon Aurigae is one of three stars representing her two kids. Epsilon Aurigae is a pair of eclipsing stars that exhibit a marked contrast. The brighter star is a yellow-white supergiant, 60,000 times as bright as our sun and with nearly thirty times the mass. Its diameter, like that of Antares, would fill the

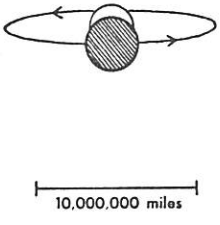


FIG. 18. *Algol*—white and red eclipsing stars.

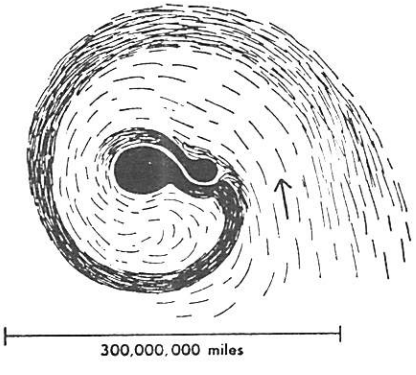


FIG. 19. *Beta Lyrae*—blue-white and yellow egg-shaped stars.

whole inner part of the solar system, and the spectroscope tells us that the surface of this star is in a state of very rapid turbulent motion.

But even the size of the bright star is dwarfed by that of its faint, almost dark companion. Here we have a spherical mass of gas so extended that if we placed it in the solar system only Neptune and Pluto, three billion miles from the sun, would be outside its boundaries. The average density of this object is less than one-millionth the density of the air we breathe, and it represents the extreme in size for stellar objects. The surface temperature is one of the lowest on record for a star, about 1,200° Kelvin, and most of the light of this star is due to the excitation of its atoms by the brilliant companion. Hence, the big star has a bright spot on the side nearest the smaller hot star. The period of revolution of this pair of stars is very long, over twenty-seven years. It takes nearly seven years for the bright star to move across behind the extended surface of its companion, while the separation between the two stars varies from five billion miles to less than three billion miles. The system is 3,400 light-years away from us.

The last star on our list, number eight, is perhaps the strangest of all. It is a type of star known as a white dwarf and has no name, only the catalogue number L886-6 *(Fig. 21)*. Dr. W. J. Luyten, an astronomer in the United States, has made a particular study of this type of star and about 200 white dwarfs are now known.

L886-6 is quite close to the solar system, only about thirty light-years away. But in spite of this proximity it appears as a star of the sixteenth magnitude, which is 10,000 times fainter than the faintest star visible to the naked eye. Its absolute luminosity is hence very low, not far from one fifty-thousandth that of the sun. On the other hand it has a high surface temperature between 8,000° and 9,000°, so that its surface brightness is considerably greater than the sun's. With a high surface brightness but very low total luminosity it must have a surface of very small area, and that means a small diameter. On calculation the diameter of this star turns out to be about 2,500 miles, less than one-third the earth's diameter and not

much bigger than the moon. It is one of the smallest stars known.

Judging by other stars of the same type we can assume for this star a mass about equal to or a little greater than the sun. This gives us a fantastically high density, somewhere in the tens-of-millions of times the density of water. A five-cent coin made of such material would weigh over ten tons, and this may seem a completely impossible value for the density of any material. It *is* impossible here on earth, but may not be so in some of these peculiar stars.

This statement may be easier to understand if you recall the nature of atomic structure. An atom itself is an extremely small unit, but most of the weight of an atom is bound up in the nucleus which is smaller still, having a diameter roughly one ten-thousandth the diameter of the atom. In ordinary material under normal conditions atoms cannot be packed together tighter than their diameters will allow. But in the interiors of certain stars conditions may arise where all the outer parts of the atoms have been stripped away, and only the nucleus is left. If then you pack these nuclei tightly together you can, theoretically, have a degenerate material with any density up to a

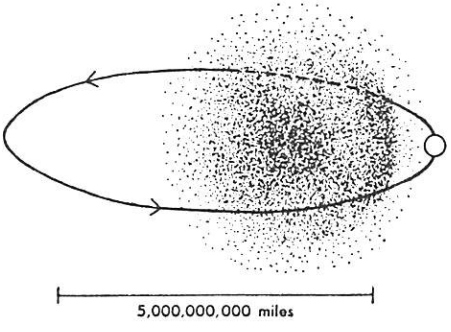


FIG. 20. *Epsilon Aurigae*—yellow and dull red supergiant stars.

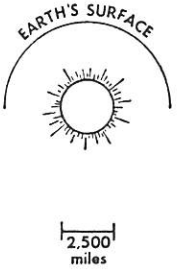


FIG. 21. *L886-6*—white dwarf star.

million million times that of normal material composed of complete atoms. This may be what has happened in the case of the white dwarfs.

And so we come to the end of our list: the supergiant, Antares, the small twin red dwarfs Kruger 60, the very massive Plaskett's Star, pulsating Delta Cephei, winking Algol, the egg-shaped stars of Beta Lyrae, the immense nebulous star of Epsilon Aurigae, and last, the very dense white dwarf L886-6.

It is natural for you to ask about the relation of one star to another. Are they all of the same age? Does one type of star evolve out of another? And if so which stars have the longer lives and which the shorter? In studying such problems for a group of stars it is usual for astronomers to plot a diagram where the absolute brightness of a star is shown in one co-ordinate against the surface temperature, or colour in the other co-ordinate. A plot of this type is known as a Hertzsprung-Russell diagram, named after its originators, the Danish astronomer Ejnar Hertzsprung and the American astrophysicist Henry Norris Russell. It is found that stars are not evenly distributed over such a diagram but tend to lie along certain preferred sequences or groupings. These are significant in relation to stellar evolution. The eight star systems we have been discussing are shown in *Figure 22* in relation to the Hertzsprung-Russell diagram for stars in general.

The subject of stellar age and stellar evolution is a very complex one. However, a great deal of progress has been made just recently, due largely to our better understanding of the conditions which govern the production of nuclear energy.

It is probable that stars are formed originally from local concentrations in the gas clouds of space. As these embryo stars contract under gravitational attraction, the temperature rises until the central portions are hot enough for a nuclear reaction to take place, and hydrogen is fused into helium at temperatures over 10,000,000°. A star, on formation, may have a relatively small mass or a relatively large mass, and its future history will depend almost entirely on the quantity of matter it contains and the composition of this matter.

The more massive stars are more prodigal of their energy resources and use up their nuclear fuel much faster than the

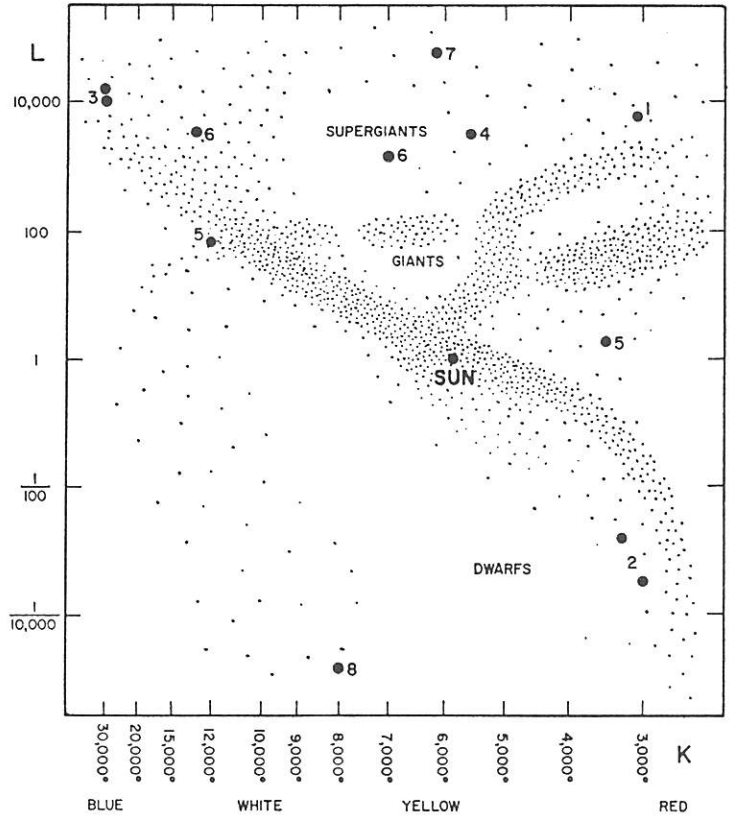


FIG. 22. The Hertzsprung-Russell diagram, where L, the absolute luminosity of a star in terms of the sun's luminosity, is plotted against K, its surface temperature in degrees Kelvin. It will be noted that stars show a tendency to group in certain areas of such a diagram. The diagonal line running from upper left to lower right is known as the main sequence and the sun lies midway along this. The eight star systems discussed are identified by number.

stars of small mass. During its life history a star may have periods when its surface temperature is slowly rising or, on the other hand, slowly falling. After the hydrogen in the centre of a star has all been fused into helium, this helium may be fused into still heavier elements at much higher temperatures. At certain stages points of instability may be reached and the star may pulsate, or even explode violently. Finally, what is left of the mass of the star may collapse into a degenerate state of matter and end up as a white dwarf, which eventually burns itself out to a dead, dark, and very dense cinder. How many of these burned out stars does space contain? At the present time no one can answer this question.

Of the stars we have visited most of them would follow completely individual life histories, owing to their differences in mass. Of the group Plaskett's Star is probably the youngest and this system, along with Epsilon Aurigae and Beta Lyrae, is burning itself out very rapidly. Stars like these cannot expect to live much longer than 10 million to 100 million years. On the other hand our sun, developing at the more leisurely pace of the less massive stars, may shine for 100,000 million years. Kruger 60 may last even longer. In the case of the tiny star L886-6 there is not much doubt that this white dwarf, with the almost unbelievable density, is shining in a venerable old age and is on the verge of burning out entirely.

What about the chances of life out among the stars? We have seen already that in the solar system only Venus and Mars hold out any hope of biologic life forms away from the earth. Many of the stars, such as the pulsating stars and the double stars, would not have stable planets circling about them and thus would not sustain life. But there must be many millions of stars that could, and probably do, have planetary systems and among these it seems probable that there must be some planets with conditions suitable for the development of life. At distances of many light years the problem of contact or even of communication betwen life cultures becomes difficult. The travel time of the signals is long, and there is the requirement that both the sending and receiving cultures have reached an advanced stage of development almost simultaneously on the basis of cosmic time scales. Civilization has existed on the earth

for only a few thousand years, and this is a short period compared to the several billion years that have elapsed since the planets were formed.

Radio telescopes as big as those now in use, or those being built, might detect artificial radio signals from planetary systems as far away as 10 or even 100 light-years. A long term radio listening program with code name OZMA is now being conducted in the United States at the National Radio Observatory in Virginia, with the hope of detecting such evidence of intelligent life outside the solar system. It is a long chance, but success on this program would be the most exciting news in a thousand years.

THE DUST AND GAS OF SPACE

6

MOST of the mass of our universe that is not in the stars exists as gas and dust between the stars. Estimates of the total quantity of this interstellar material range all the way from five per cent to fifty per cent of the total mass in the universe. If the steady-state model of the universe (*page 113*) is correct, gas may account for much more than fifty per cent of the total mass. The word gas refers to matter where the individual atoms or molecules are separated and move independently of each other. The word dust is used to refer to matter in the form of small solid particles with dimensions considerably larger than those of atoms and molecules.

In speculating on the origin of stars it is usual to assume that initially they developed from concentrations in a large, diffuse cloud of gas. This suggests that a gas cloud was the original, or at least an earlier, state of matter, and that the stars evolved from it. On the other hand our sun is continually projecting streams of gas into the solar system, and other stars, much brighter than the sun, are even more active in this regard. Obviously then some of the matter we now find between the stars originated in the stars. As a matter of fact interstellar material with this type of origin may be quite important in our study of the evolution of the universe. It is quite possible that some of the heavier elements owe their origin chiefly to nuclear reactions that have taken place inside stars.

Most of the stars appear the same year after year. If they do change, the process is so slow that even centuries of obser-

vation would show no great difference. But every now and again a bright star suddenly appears where no object was previously visible. This is a so-called new star, or nova. The name is a bit misleading as the star has been there all the time, generally very faint and visible only in a large telescope. But all at once it reaches an unstable point in its development, and within a few hours it increases in luminosity to over 50,000 times its previous brightness. Such an event is an explosion of truly cosmic proportions. At its brightest a nova shines with an absolute luminosity something like 100,000 times that of the sun.

A bright nova appeared in the constellation Perseus in February, 1901, and another in Aquila during June, 1918. These both became as bright as any of the stars we see except for Sirius, the Dog Star. But after a couple of months they faded back into obscurity again. Analysis of the light of these novae with the spectroscope showed that when they exploded they threw off great shells of bright gas that moved outward at speeds up to 2,000 miles per second. Many years after the original outbursts the remnants of these gas shells could still be seen in the telescope as areas of faint nebulosity around the two stars (*Fig. 23*).

Tremendous as these nova outbursts are, we sometimes see an explosion in space which is 10,000 times more powerful. This is called a supernova and the brightest supernova can shine with a light equivalent to 1,000 million suns. On November 11, 1572, a star that could be seen in broad daylight suddenly appeared in the constellation Cassiopeia. This was a supernova and was studied in detail by that most assiduous observer of the heavens, the Danish astronomer Tycho Brahe. Unfortunately, this event occurred before the telescope was invented and so our knowledge of Tycho's Star, as it is called, is restricted to what could be observed with the naked eye. The star faded slowly and remained visible for nearly a year and a half, after which it was too faint to be seen without instrumental aid. Now, nearly four centuries later, we cannot identify it as there are a number of very faint stars in the position described by Tycho.

However, looking in a different part of the sky, we can still see the remains of another bright supernova of the past.

In the constellation of Taurus the Bull, near the tip of one of the bull's horns, we see an object consisting of weirdly shaped filaments of gas. This seems to bear some resemblance to a crab, and so it has been called the Crab nebula (*Fig. 23*). Now the old records of both the Chinese and the Japanese state that in approximately this same position a very bright new star appeared in the sky in the year A.D. 1054. It reached a brightness equal to Jupiter and then eventually faded away. Careful observations, made over the last fifty years, have shown that the Crab nebula is gradually expanding at a rate which indicates that it originated at a point near its centre 900 years ago. This pretty well confirms the hypothesis that the Crab nebula is the remains of the medieval supernova. The speed of expansion of the nebula is 800 miles per second, and its diameter is now almost four light-years, that is roughly the distance from the solar system to the nearest star. Think of an explosion big enough to fill a space of this volume!

Both types of nova explosions occur because a star loses the balance between its nuclear energy production and the radiation of this energy into space. In the case of the ordinary nova the event is probably more superficial and associated chiefly with the outer layers of the star. In the case of the supernova it is deep seated and originates in the star's central core. It is suspected that most novae are repeaters, and blow off their outer layers at intervals of a million years or so, while it is not likely that a star can be a supernova more than once. As far as we know only a small percentage of the stars become novae. In our own star system, or galaxy, it is estimated that some twenty or thirty nova explosions occur every year, but supernova explosions are much rarer and according to latest calculations we probably have only two or three of these every century. A large percentage of the latter will be hidden by obscuring matter and will not be seen from our position in the galaxy.

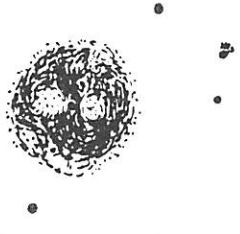
There is another class of object in space which may be closely related to the exploding stars and their clouds of gas. Here and there we find a hazy, symmetrical form of a circular or oval shape. About 500 of these objects are known and they are called planetary nebulae, not because they have any physical

M1 (CRAB NEBULA)

NOVA PERSEI

M57 (RING NEBULA)

NGC 6543



M97 (OWL NEBULA)

NGC 7009 (SATURN NEBULA)

FIG. 23. Examples of associations of gas showing some degree of symmetry and generally associated with a single star near the centre.

connection with the planets but because many of them look something like faint planets when seen in small telescopes. Actually a planetary nebula is a complex or multiple gas shell with a very faint star at the centre. The best known is the Ring nebula in Lyra, while among the others are the Owl nebula, the Saturn nebula, the Dumb-bell nebula, and so on *(Fig. 23)*. In each case, the name gives an indication of the general appearance.

To fully understand what these objects are it is necessary to analyze their light. Most luminous sources send out a great mixture of various colours of light, which correspond to different wave-lengths, and which can be spread out in a spectrum by using a spectroscope. A very hot solid object, or a gas of high density, sends out all colours of light and the spectrum is a continuous band of colour. Such light is emitted by an ordinary incandescent light-bulb with a hot tungsten filament inside. In contrast, a glowing gas of very low density sends out light consisting only of specific colours that are characteristic of the types of atoms in the gas. This is called a bright-line spectrum and an example of a source of this nature is a fluorescent lighting fixture or a neon sign. Here the glowing gas is at such a low density that the atoms can act individually, and they shine with the particular wave-lengths of the elements involved.

The planetary nebulae were found to shine with the last-named type of light, and the familiar lines of hydrogen and helium were easily identified in their spectra. But the surprising thing was that most of the light showed a pattern of colours never before observed. In particular there were two strong lines in the blue-green and three in the violet that were present in the light of practically every nebula, and there was not the slightest hint as to what element might produce them. Astronomers began to talk about the possibility of nebulium, a new element that might exist only in the nebulae.

Then, thanks largely to the work of I. S. Bowen at the Mt. Wilson Observatory in California, it was realized that the unrecognized type of light was produced by well-known, familiar atoms shining in very unusual conditions—at least unusual as far as our experience on the surface of the earth is concerned.

The strongest of the unidentified bright lines in the planetary nebulae were produced by three atoms, oxygen, nitrogen, and neon. Who would have guessed that these celestial objects would hang out a neon sign to advertise their compositions to astronomers on earth. When I said the luminosity of the nebulae was something like fluorescent lighting, my comparison was more apt than you may have realized.

It may seem strange that these three familiar atoms remained unrecognized for such a long time. As a matter of fact they had all assumed very excellent disguises. In a neon sign on earth the neon atom shines with a red light while in the nebulae its chief radiation is a rich violet colour. Oxygen turned out to be the element producing the two strong blue-green lines and the other two strong lines in the violet.

Why do we not observe this type of light when we study neon and oxygen atoms in the laboratory? The most important factor is one of size. The planetary nebulae have diameters ranging up to half a light-year. The important difference between the gas in the laboratory and the gas which is shining in the nebulae is that on earth we can only experiment with a very small volume of gas in a glass tube, while out in space we are looking through a sphere or shell of gas two million million miles across. Under these conditions we can see certain colours or wave-lengths of light which stand only a very small chance of occurring. Physicists, accustomed to working in laboratories, called these colours forbidden lines, but the emission of these wave-lengths is not actually impossible, only highly improbable. When we look through a million million miles of gas enough atoms in the long column will be shining with the very improbable light to be seen. On the other hand the atoms in space are so widely separated that often they will not shine with the light we are accustomed to see from atoms in the laboratory.

Although the stars at the centres of the planetary nebulae are inconspicuous to the eye, it is these peculiar stars which provide the energy which makes the nebulae luminous. These stars are very strong in ultra-violet light, invisible in our telescopes. Ultra-violet light has high energy and this energy is

pumped into the atoms of the nebular gas, making it possible for them to fluoresce with light in the visible part of the spectrum.

The gas clouds we have been discussing are in the form of shells around very hot stars, and it is logical to assume that they originated in these stars at some time in the past. In fact, in the case of some of the novae, we have been able to observe the actual formation of gas shells.

But the material in these shells represents only a very small percentage of the dust and gas in space. By far the greater part appears either as bright or as dark clouds of irregular outline, many of these looking remarkably like the clouds in our own atmosphere. In distant space we even see clouds with a silver lining. One important difference between the clouds in space and those on earth is the time scale. Our local clouds are transitory and change their form every few seconds, while the space clouds look much the same century after century. This is not because they are not in motion—the space clouds may have turbulent velocities of five miles per second or more. It is simply that their distances from us are so large that even these velocities will not have any great effect on their shape over intervals of many years, and as a result we have plenty of time to study them in detail.

Let us go out and take a look at the night sky. If you observe from a dark location, preferably away from city lights, you cannot fail to notice a faintly luminous ragged band of light which crosses the heavens from one horizon to the other. Throughout most of the summer evenings this appears high overhead, arching from north-east to south-west, while during the winter season it extends from north-west to south-east. This is the Milky Way, renowned in mythology as the pathway of the gods, or the road to heaven traversed by departed spirits. Milton, in *Paradise Lost,* makes reference to it as follows:

> A broad and ample road, whose dust is gold,
> And pavement stars, as stars to thee appear,
> Seen in the galaxy, that milky way,
> Which nightly, as a circling zone, thou seest
> Powder'd with stars.

The light of the Milky Way comes mainly from stars too faint to be seen separately by the naked eye. This circle of

faint stars marks out the great framework of our own star system, consisting of some hundred thousand million stars. We refer to it as the Galaxy, a term derived from the Greek word γάλα, meaning milk.

Most of the bright and dark clouds or nebulae of irregular outline are found in and near the Milky Way. Some have been named after their chance resemblance to certain forms. Thus among the bright clouds we have the North America nebula, the Network nebula, and the Pelican nebula, while some of the dark clouds are called the Cone nebula, the Coalsack, and the Horsehead nebula. The southern part of the Milky Way seen in summer, that runs from Cygnus down through Sagittarius, is divided into two by a dark lane known as the Great Rift. This is an immense cloud of obscuring matter relatively close to the solar system, and it hides the light of the stars behind it. In some areas the dark clouds of space are completely opaque, and allow no visible light to penetrate from the far side. Others only dim the light of the stars behind them, and in this case the stars usually look redder than normal.

Is it possible to learn anything about the material in these absorbing clouds? Before I answer this question I want you to think of a somewhat similar situation on earth. Sometimes we have a cloud that completely obscures the sun. At other times we may have a fog bank overhead, which dims the brilliance of the sun but still allows us to see it quite clearly as a white disk. Again, when the sun sinks to the horizon on a clear day, it may be dimmed to a fiery red disk as it sets. These various effects are due to a phenomenon we call the scattering of light.

In the case of the dense cloud all the light from the sun is scattered and none of it gets through the cloud directly to reach our eyes. All we see is the general luminosity of daylight. The fog on the other hand scatters some of the sunlight, but the rest gets through and reaches the eye, so we see the sun's disk dimmed. In this case all the colours of light are scattered in the same proportion and the colour of the sun is not materially changed. However, in the third case, when the sun is near the horizon on a clear day, the blue light is scattered much more than the red light with the result that most of the

blue light does not reach our eyes and the sun looks red. This is called selective scattering, that is certain wave-lengths of light are affected more than others. It has been found that dust particles bigger than one-thousandth of an inch in diameter scatter all colours equally, but when the particles are 10 to a 1000 times smaller than this, the blue light is scattered twice as much as the red. For even smaller sizes, corresponding to atoms and molecules, the blue light may be scattered ten to twenty times more than the red light.

Most of the scattering of starlight by the dust of space seems to be of the type that would be produced by particles between a thousandth and a millionth of an inch in size. Recent work has suggested that particles considerably smaller than this may also be present, and that some dust particles may have an elongated or needle-like shape. Whatever the exact form of the dust, it is believed that small particles are formed out of the gas of space by a tendency of the atoms of hydrogen, carbon, nitrogen, and other elements, to clump together and to build up larger units. This process may be assisted by particles formed in the atmospheres of cool stars.

The dust reveals itself in another way, which has a good analogy here on earth. On a foggy night you see a glow around every street light since the fog particles reflect light. In the same way dust clouds in space near bright stars reflect the light of these stars. A beautiful example of this is the little cluster of stars called the Pleiades, or the Seven Sisters. Long-exposure photographs of this cluster show hazy clouds around all the brighter stars. When we analyze the light of these misty halos we find that it is the same as that of the stars, which indicates that it is reflected light. And just as in the case of the street lights, the brighter the stars, the greater the distance to which the illumination extends. The brightest stars in our system will illuminate this interstellar material out to a distance of over thirty light-years from the star. However, an average star like our sun will only illuminate it out to a distance of a quarter of a light-year. Dust that does not happen to be near enough to a star to be illuminated remains as a dark cloud, and photographs show that some of these dark masses of dust have

relatively sharp edges, the Horsehead nebula being the most famous example of this.

We have all heard the expression 'where there's smoke there's fire'. In space at large this could be paraphrased by saying 'where there's dust there's gas', since the close association of dust clouds and gas clouds is clearly indicated by astronomical observations. If, as suggested earlier, dust is forming out of gas, it is not exactly surprising that we find both in the same regions of the universe.

The gas of space can be recognized in a number of ways. We have already seen how the ultra-violet light from hot stars will cause the emission of visible light in an extended shell around the star. The same effect is found in the irregular gas clouds. If they happen to be near hot stars the atoms in the gas will be excited, and will shine in the same way as does the gas in a planetary nebula. The best example of this is the great nebula in Orion that marks the jeweled sword hilt near the belt of the Hunter. This is one of the nebulous objects that can be seen quite well with small telescopes, and in photographs it looks just like the great swirling turbulent mass of gas it is. Four blue stars with high surface temperatures are located near the centre of the Orion nebula, and these provide a large portion of the energy that keeps it shining.

Throughout the universe hydrogen is the commonest element. The hydrogen atom is the simplest atom and consists of one positive electrical charge and a negative charge, or electron, to balance it. In most parts of space the hydrogen atoms are cold and dark and in a state of very low energy, but near the hot stars there is enough energy to remove the electrons from the hydrogen atoms. This hot hydrogen is said to be ionized, and when the wayward electrons rejoin the ionized hydrogen atoms, the characteristic light of hydrogen is given out. This process is going on continuously in regions of space near the hot stars. Whether a gas cloud in space shines with its own light or not depends on the surface temperatures of the stars embedded in it. If we find stars hotter than 18,000° Kelvin, the gas near them will fluoresce with the characteristic atomic radiations I have already described. For the cooler stars below

18,000° there is not enough energy to excite the gas to shine, and here we see only the reflected starlight from the dust clouds, as was noted in the Pleiades.

It is natural to inquire as to just how concentrated this space material is. According to the standards we are accustomed to, it is very rarified indeed. Let us start with the air we breathe at sea level as a standard for comparison. It is roughly one-thousandth the density of water. At a height of sixty miles above the earth the density of the atmosphere is one-millionth the density of the air at sea level. We can produce a density ten million times smaller still with good vacuum pumps in a physics laboratory. But the density of a typical gas cloud in space is ten million times rarer than this laboratory vacuum, while the average density of space dust is lower still, probably not much more than one per cent of the gas density. If you have been keeping track of the powers of ten in what I have just listed you will find that the average density of gas in the plane of the Milky Way is equal to the density of water divided by ten raised to the twenty-third power, while the density of dust is that of water divided by ten raised to the twenty-fifth power.

Even so, however, space is far from empty. Suppose we take a typical cubic yard of space in the plane of the Milky Way. On the average we will find in this cube about five million hydrogen atoms. The number of helium atoms present is somewhat uncertain but they are probably next to hydrogen in abundance. There will be roughly 1,000 atoms each of oxygen, nitrogen, and carbon, while magnesium and silicon, and possibly sodium and neon also, contribute 100 atoms each. Then there will be smaller quantities of other elements, some simple molecules, and a large number of electrons. The dust is much less evident; there is only one grain in every thousand of our cubic yards. Yet even this small amount is quite sufficient to cause the obscuration and reddening we see in our galactic system.

The interstellar gas shows a tendency to gather into clouds of higher density than the average, and in certain areas of space it is possible that stars are forming out of the gas. The region of the great Orion nebula is quite likely a place where

stars are being born at the present time, as here we find a large number of very luminous and hot stars of the type believed to be relatively young.

The gas in space does not produce visible obscuration in the same way as the dust particles, but its effect can be seen when we study starlight with the spectroscope. The spectrum of a star, like the spectrum of the sun, consists of a band of colour covering the entire range from violet to red. But on this band we find certain missing wave-lengths or colours that appear as dark lines on a bright background. These are characteristic of specific atoms which are in the outer layers or atmosphere of the star, and which are interposed between us and the hotter lower layers of the star. Starlight, when analyzed, turns out to be quite complex. If we have atoms in space between us and a star, they also may add their contribution to the star spectrum in a similar way to atoms in a very extended stellar atmosphere. We can usually identify the features added by the space gas, as the lines will look somewhat different to those originating in the star itself, and will give a different velocity in the line of sight. The calcium and sodium atoms in space show up particularly well in this way and have been studied in detail by astronomers in both the United States and Canada.

The stars, and the clouds of dust and gas in our galactic system, have their own individual motions, but over and above this there is a general motion of the whole system. Both stars and interstellar matter show the same basic rotation about the distant centre of our star system. In fact it was the motions of the stars which first clearly demonstrated that there was a distant massive centre to the galaxy. Radial velocity observations of stars and gas clouds, made at the Dominion Astrophysical Observatory near Victoria, B.C. by J. S. Plaskett and J. A. Pearce, played a vital role in charting the position of this centre, and in finding the relation of the sun to it.

The problem of locating the centre of the galaxy is not an easy one. With optical telescopes it is not possible to see it as there is too much dust in the way. We have to deduce where the centre is by a study of the star motions in our immediate neighbourhood. I think you will be able to visualize this more easily if you imagine yourself at an amusement park where

there is a ride that consists of a series of concentric tracks upon which a large number of small cars all go round in the clockwise direction. You get on a car partway out from the centre to the edge. It's a very foggy night so you can't see the centre of the ride, but you do see the cars near you. You note that those on your right seem to be passing you as a result of being on a shorter track. At right-forward they move almost directly away from you while to right-rear they are approaching. On the other hand, you keep about the same distance from the car immediately ahead but you approach or overtake the cars to left-forward, pass the cars to your left, and move away from cars to left-rear. If you carefully measure the relative motions of all the cars around you, you can draw some conclusions about the distance of the centre of the ride from your particular car even though you never see the centre itself.

This is the type of reasoning that led to a knowledge of the fact that the solar system, along with all the other stars and clouds in our part of space, is moving at a speed of over 130 miles per second in the direction of Cygnus, the Northern Cross or Swan. This general motion is part of the rotation around the centre of our star system, and takes place in the plane of the Milky Way. The centre is 26,000 light-years away towards the constellation Sagittarius. It will take us well over 200 million years to make one complete circuit, and like the cars on the midway ride we are all moving clockwise when viewed from the top or north side of the Milky Way.

The general conclusions just mentioned were reached over thirty years ago as a result of the optical study of stars within a few thousand light-years of the sun. During the last ten years they have been verified by a completely independent series of observations made with radio telescopes. It was in the spring of 1951 that Harold Ewen, a graduate student at Harvard University, first recorded the radio signals from hydrogen atoms in space, using a strangely shaped horn that looked like a futuristic model of *His Master's Voice*. We have seen that most of the atoms in space are cold, and do not either emit or absorb light in the visible part of the spectrum; hence, they are invisible. But the cold hydrogen atoms do, once in a long while, send out energy in the radio spectrum

FIG. 24. Clouds of hydrogen gas in our galaxy, adapted from plots by J. H. Oort, G. Westerhout, and G. W. Rougoor, at the Leiden Observatory. The position of the sun is indicated by a cross.

on a wave-length of 8.3 inches. There are several million hydrogen atoms in each cubic yard of the space clouds, so even if each hydrogen atom emits radiation only at very long intervals, there will always be some atoms broadcasting on this wave-length.

By recording this eight-inch radiation, and studying its velocity variations over the sky, the hydrogen clouds of our galactic system have been mapped out. The wonderful part about this method of charting the galaxy is that the dust clouds, which hide the light of the galactic centre in optical light, are transparent to the hydrogen eight-inch radio wave-lengths. Hence, it has been possible to observe directly the centre of our system, and to map out the long spiral condensations of hydrogen gas that encircle this centre (*Fig. 24*). The stars show a tendency to cluster along these arms of gas, and the sun itself is located in one.

The whole flattened disk of gas and dust and stars forming our galaxy has a diameter of about 80,000 light-years, and a mass of some 100,000 million suns. The old 'pathway of the gods' has in truth acquired vast proportions, and our entire solar system is but a tiny speck in this vastness.

GALAXIES OF STARS

7

THE stars we see, even on the clearest night, all belong to our own star system or galaxy. This galaxy has the form of a large flattened disk and is outlined by the Milky Way. In the galaxy are located some 100,000 million stars, and between the stars is finely divided matter in the form of gas and dust. We have found that this star system of ours has the immense diameter of 80,000 light-years. This means that light, which can girdle the earth seven times in less than a second, would take 80,000 years to travel from one side of the galaxy to the other. But this is only the beginning of immensity because our galaxy, with all its stars and gas and dust, is only one of a great multitude of other similar galaxies that we observe in the depths of space far beyond the limits of our own star system.

During the evenings of late summer the constellation Andromeda, the Chained Maiden, rises in the north-east. Above the three principal stars in this figure you can just detect with the naked eye a little misty patch somewhat elongated in shape. This is the Great nebula in Andromeda, one of the closest of the other galaxies. If you take a trip to the southern hemisphere two more of our neighbouring galaxies can be seen: the famous clouds of Magellan, or the Magellanic Clouds. These look like detached portions of the Milky Way, and were named after the Portuguese navigator who in the sixteenth century led the first expedition to circumnavigate the globe. The Andromeda nebula and the two Magellanic Clouds are the only external galaxies, or island universes as they have often been

called, that are visible to the naked eye. In telescopes many more can be seen visually as small hazy objects with little detail. But only photography gives us a true impression of the actual numbers of these external star systems. They are found in the hundreds-of-thousands, and in certain parts of the sky, among the faintest objects that can be photographed with large telescopes, there are actually more galaxies than stars recorded on the plates. When we realize that each one of these galaxies is a great star system in its own right, it is almost more than the mind can comprehend.

If I were asked to pick the most universal and significant units in our physical world I would say atoms, stars, and galaxies, on the basis of universality, and I would add men on the basis of subjective significance, since without man's ability to reason there would be no discussion at all. Now it so happens that these four units, atoms, men, stars, and galaxies, form a rough sequence of increasing size which, in very round figures, has equal steps. You could lay 10,000 million atoms in a row on a man's body. If you placed 10,000 million men in a row they would reach from side to side of an average star, and if you placed 10,000 million stars side by side they would extend across an average galaxy. Since atoms, men, stars, and galaxies, all vary a good deal in size, one should not attempt to apply this yardstick in too exact a manner.

What are some of the characteristics of these galaxies of stars that we observe in such number? There can be no doubt that the most obvious feature seen in the majority of galaxies is a spiral structure. This spiral form was discovered in 1845 by the Earl of Rosse, an Irish nobleman who was an amateur astronomer with plenty of money. He had erected at Birr Castle a reflecting telescope with a metal mirror six feet in diameter. Just two months after this great instrument was put into use it was found that a nebula in Canes Venatici, the Hunting Dogs, not far from the Big Dipper, had spiral arms winding out from the centre, and this is still known as Lord Rosse's spiral. In the next few years some fourteen nebulae were observed to be of the spiral type. However, the spiral form of these objects is revealed much better in photographs and today the study of

their structure is carried out entirely by means of photography. The term spiral nebula, used for many years in referring to these systems, has now been replaced by the designation spiral galaxy.

About one-fifth of the galaxies show no spiral structure at all. A few of this group are quite irregular in shape but most have a regular outline that varies from circular through elliptical to a narrow spindle shape. These are called the elliptical galaxies but in reality most of them probably approach a disk-like form. When seen from a direction at right angles to the plane of the disk they appear circular, and when seen edge-on they appear elongated.

The elliptical galaxies exhibit practically no detail. Their surface brightness is greatest at the centre and grades down to very low values at the outer edge. Two good examples of elliptical galaxies appear as companions to the Great nebula in Andromeda. In most photographs these elliptical systems look like hazy, symmetrical gas clouds but the nearby examples have been resolved into stars with the 100-inch telescope on Mt. Wilson, and with the 200-inch telescope on Mt. Palomar. The stars are relatively close together at the centres of such galaxies but thin out greatly towards the edges.

One of the pioneers in investigating the galaxies was the late E. P. Hubble of the Mt. Wilson and Palomar Observatories. He suggested a simple observational classification for these systems, based entirely on the dominant visual characteristics *(Fig. 25)*. The elliptical galaxies were graded according to the degree of their apparent flattening or ellipticity, and the spiral galaxies were graded according to the prominence of the central nucleus relative to the arms. An interesting variation appears in about a third of the spirals, where the arms do not curve directly out of the nucleus or central core, but seem to start from the ends of a straight bar running through this core. These are called the barred spirals and they have a somewhat artificial appearance.

Strangely enough, in spite of many suggestions and much theorizing, no perfectly satisfactory explanation has yet been advanced to account for the continued existence of spiral arms

in such a large percentage of galaxies. Current thinking tends to the belief that magnetic fields in space may have a lot to do with maintaining a spiral structure in star systems, but it is too early yet to say anything definite on this subject. It is worth noting, however, that the effects of magnetic fields are entering more and more into the theoretical discussions of certain features of our universe, and the importance of such considerations has only been realized in recent years.

One thing we do know about the galaxies is that, like immense celestial pin-wheels, they are rotating about their centres, and where spiral arms are present, the arms trail, according to most investigators. As in the solar system the central portions of the galaxies have a shorter period of rotation than the outer parts, so they are continually winding themselves up. One of the problems that has to be solved is why the spiral arms have not been wound out of existence in the billions of years since the galaxies were formed.

In any system of bodies revolving around a common centre of gravity we can tell something about the masses involved by the application of Newton's law of gravity. The greater the mass, the more rapid will be the revolution. Hence, the motions of the stars about the centres of the galaxies enable us to determine approximate masses. The average galaxy has a mass equivalent to 10,000 million suns. Some small dwarf galaxies have a mass considerably less than one-tenth this average value, while very large galaxies, like the Andromeda nebula and our own galaxy, have masses ten times the average, or 100,000 million suns.

The visible light from galaxies consists mostly of the luminosity of all the stars contained in each system, blended together, while a small fraction of the light comes from the interstellar material that lies in the arms of the spiral galaxies. When we study the galaxies with a radio telescope we find that the cold hydrogen gas lying between the stars sends out a radiation on a specific wave-length of 8.3 inches. This eight-inch hydrogen radiation has made it possible for us to trace out the spiral arms in our own galaxy, as the gas always lies thickest along the arms *(Fig. 24)*.

But there is another type of radio energy emitted by both our galaxy and many of the other systems. It originates from a roughly spherical volume, or halo, considerably larger than the visible disk of stars that makes up a galaxy as we see it in photographs. In other words a galaxy has about twice as big a diameter when viewed with a radio telescope as when photographed. It is now believed that this invisible halo radiation comes from an immense cloud of electrons, that is small, negatively charged particles. These acquire high energies from the cosmic rays of space and such electrons, if placed in a

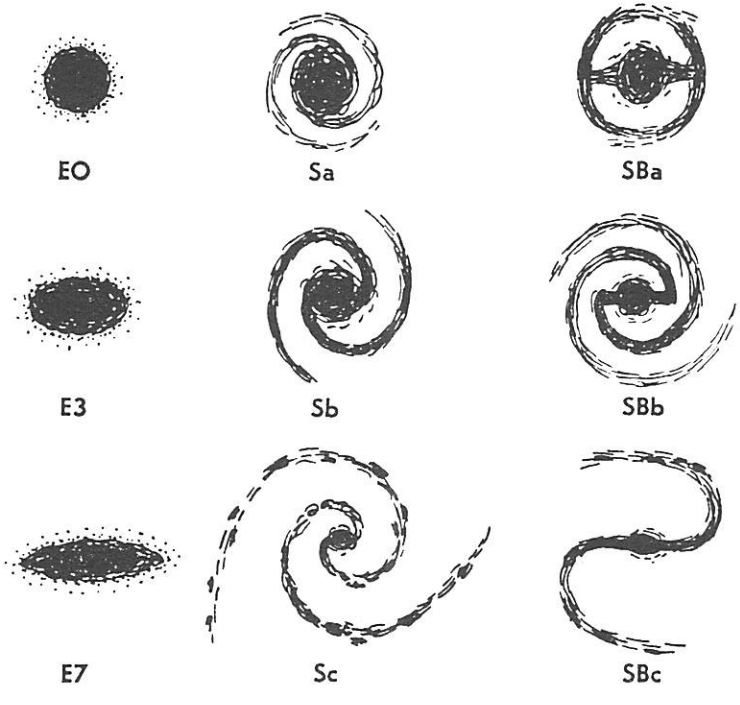


FIG. 25. A basic classification of the extragalactic nebulae, or galaxies, by E. P. Hubble.

magnetic field, will produce radiation. Hence, the halo radiation from a galaxy gives evidence of two phenomena associated with the galaxy: a cloud of high energy electrons, and a general magnetic field.

I have already noted that the majority of galaxies show a spiral structure, while most of the remainder, about twenty per cent, are elliptical objects with no evidence of spiral arms. However, the elliptical galaxies look very much like the centres of the spiral galaxies minus the arms. Suppose we examine more closely the differences between the elliptical and the spiral star systems.

We can start by looking at the types of stars involved. The term giant refers to a star which has a very high absolute luminosity, in other words a light source with a high candle power, and this generally means a relatively large mass as well. The sun is located in one of the spiral arms of our own galaxy, and in the general neighbourhood of the sun we find some very luminous blue-giant and supergiant stars with high surface temperatures. Along with these we have other types of stars such as red giants, yellow stars of average brightness like the sun, red dwarfs, and white dwarfs, and so on.

When the individual stars in the elliptical galaxies were first studied, astronomers were surprised to find there were no blue giants at all in these systems. The brightest stars were the red giants, and these gave the elliptical systems a slightly redder colour than the spirals. It was also found that the central cores of the spiral galaxies were like the elliptical galaxies, and contained no blue giant stars. Some other interesting differences turned up. The elliptical galaxies, and the central parts of the spiral galaxies, contained practically no gas or dust among the stars, while the spiral arms in galaxies had large amounts of both gas and dust.

Thus, we find in space two completely contrasting arrangements of matter. On the one hand we have the spiral arms of galaxies with many types of stars, including bright blue giants, and quantities of gas and dust between the stars. On the other hand we have the elliptical galaxies and the central cores of the spirals, with no blue giants and little gas or dust. For convenience in reference the two types of stellar associations have

been named Population I and Population II. Population I occurs chiefly in spiral arms and corresponds to what we find in our portion of space, where both blue giants and gas and dust are present. Population II is what we find at the Galactic centre, in the centres of other spiral galaxies, and in the elliptical systems. Here neither blue giant stars nor gas and dust are found. The late Walter Baade, of the Mt. Wilson and Palomar Observatories, was chiefly responsible for developing this very important concept of the two types of stellar communities.

It is natural to ask whether there is any explanation for the two populations in space. The origin of this phenomenon must be very basic, and must depend on the way star systems have evolved from the original state of matter. There are many puzzles still to be solved in this connection but on certain facts there is general agreement.

Population II lacks the bright blue giant and supergiant stars. Stars of this type are radiating energy at a very high rate, and they are using up their resources of nuclear fuel so fast that they cannot be very old compared to objects like the sun. These bright blue stars are considered to be the youngest members of the stellar company. It is a very significant thing that gas and dust in any quantity are missing from exactly the same formations that have no blue giants. This lends weight to the hypothesis that stars condense out of the gas and dust of space, and it is logical to find very young stars where there is a good supply of this star-forming material, but no young stars where this material has all been used up. We thus have the picture of Population II as consisting only of middle-aged and very old stars that have existed for thousands of millions of years, while Population I contains both the old and the young, and has many regions where even now stars are being born. The great swirling mass of gas and dust that centres around the nebula in the constellation Orion is such a region.

But we are not yet certain of the reason why some galaxies contain nothing but an aging population while others have in addition the younger, more varied, and active population of the spiral arms. The best guess at present is that the answer will be found when we consider the action of one galaxy on another.

We will come back to this point a little later. In the meantime it may give us some satisfaction to realize that the sun, although itself a middle-aged star, is a member of the younger and more virile type of population in our galaxy. The division of stars into populations is a statistical procedure and in the case of many individual stars it may be difficult or impossible to decide which population they belong to.

I have said a lot about galaxies as individual units, and it is time we paused for a moment to review the contents of an average galaxy. Let us take the typical spiral system. At the centre we have a massive core formed of very old stars and around this a flattened disk of spiral arms, with an over-all diameter somewhere in the range between 10,000 and 100,000 light-years or more. The stars in this disk exhibit a great variety, not only in colour and size but also in behaviour and in association with their neighbours. We find rapidly pulsating white or yellow stars and others that are red and vary slowly in luminosity. Some stars emit great quantities of gas, either steadily or in tremendous flares and outbursts. Many stars pair up with a companion, and we have every conceivable combination of two or more stars revolving about mutual centres of gravity. Often the tidal forces in these systems become so extreme that the stars are deformed, and great streams of gas spiral out into space and envelop the surrounding region. Ghostly shells of gas around certain stars appear as remnants of past activity, and bright and dark nebulosities lie thick along the spiral arms.

Then we have the larger associations of stars: clusters like the Pleiades, the Hyades, the Double Cluster of Perseus, and others, most of them lying near the basic plane of a galaxy. And there is another kind of star cluster that is not confined to the general plane of a galaxy. I refer to the globular clusters, spherical associations of some 100,000 stars each. These are distributed widely like the outer framework of a star system, and it was a study of the globular clusters which first suggested to the American astronomer Harlow Shapley the great extent of our own galaxy. In photographs of the closer galaxies the globular clusters can be seen like little hazy dots grouped around each star system. And outside the globular clusters

there is an invisible halo of atoms and electrons, extending out into space beyond the visible portion of the system. Such is a typical galaxy.

What about the relations of the galaxies to each other. When we study their distribution in space we find a definite tendency for them to cluster together. This is somewhat analogous to the behaviour of stars, and as a matter of fact, of men and of atoms as well. Our own galaxy belongs to a local cluster of at least seventeen star systems. Apart from ours I have already mentioned five of these systems, the Andromeda nebula and its two elliptical companions, and the two Magellanic Clouds. The seventeen galaxies of the local group occupy a somewhat elongated volume of space roughly two million light-years long. We can best visualize the spacing by adopting a scale of one inch to 10,000 light-years. Now, take seventeen disk-shaped objects of assorted sizes ranging from a twelve-inch cake plate for the Andromeda galaxy, and an eight-inch dessert plate for our own system, down through saucers and coins of various sizes to the heads of small thumb tacks for the smallest galaxies. Suspend these at random in a room ten by twenty feet in size, placing the two largest plates near opposite ends of the room, and you have a scale model of our local cluster of galaxies.

Other clusters of galaxies are larger and contain more members. The closest large cluster outside our local group is called the Virgo cluster because it lies in the direction of the constellation Virgo, the Virgin. Almost in the same general direction is the much more distant Coma cluster, named after the little constellation of Berenice's Hair. A scale model of the central part of the Coma cluster could be made by taking the same assorted plates, saucers, coins, and thumb tacks we used before, and scattering 500 of them in a hall fifty feet square with a very high ceiling.

Twenty or more clusters of galaxies have now been studied, and these range in distance out to those where the brightest galaxies of the cluster can just be photographed with the 200-inch telescope as tiny hazy dots on the negatives. Taken by themselves we would not know what these tiny dots were but fortunately we have a steady progression of photographs from those of the nearby galaxies, where we can study individual

stars, down through smaller and fainter images with less and less detail to the minute records of the most distant galaxies that can be detected.

This question concerning the distances of the galaxies is very difficult. It is possible to determine the relative distances of the various clusters of galaxies by tabulating the apparent size and brightness of the most prominent members of the cluster. Although individual galaxies vary greatly in size and type there seems to be a fairly uniform upper limit of absolute brightness for the big ones in a cluster. The fainter these appear the more distant the cluster. But to arrive at the absolute distances of the galaxies is a much bigger problem. During the last ten years our estimate of the distances of these clusters of galaxies has been steadily going up, even though the fundamental observations upon which these distances are based have not been altered.

We must make the assumption that the physical characteristics of the galaxies at the limits of observation are the same as those in our own neighbourhood. From the evidence available this seems a sound hypothesis, at least in the first approximation. The latest estimate of the distance of the Virgo cluster, the closest to us, is about fifty million light-years while the Coma cluster is just under 300 million light-years away. The light of the Coma cluster, observed today, has been on its way to us for close to 300 million years, and we see this group of galaxies as it was when the carboniferous forests of tree ferns flourished on earth long before the age of the dinosaurs.

But the Coma cluster is among the three or four closest clusters of galaxies. The others are much further away and have distances extending up to several billions of light-years. And yet we may be recording systems far beyond this visible limit. The apparent paradox arises as a result of the use of radio telescopes, which record the invisible radio waves from the universe around us. I have already mentioned in these lectures several sources of radio waves from space. There is our own sun for example, and there are the atmospheres of some of the planets. Then there is the hydrogen gas in our star system that is broadcasting on a radio wave-length of 8.3 inches, and we receive a more general type of radio energy from the Milky

Way and from the electron halo enveloping the Milky Way. But some of the strongest radio signals come from none of these sources. As soon as radio astronomers started to make a general survey of the sky in various radio wave-lengths they detected many sources of radio waves that were very small and had a fixed position among the stars. These were called 'radio stars', and for most of them there was no visible object in the direction in space from which the radio waves seemed to come.

Unfortunately radio telescopes are not able to fix the position of radio sources with the accuracy possible in optical work. This adds to the problem of identification. The first radio star to be recognized was found in 1944 by the pioneer radio astronomer, Grote Reber. It is located in the constellation Cygnus the Swan, and has been named Cygnus A. When the position of Cygnus A had been determined to a reasonable accuracy with the world's most powerful radio telescopes, then the 200-inch telescope on Mt. Palomar was used to examine this region of the sky, and a very faint peculiar galaxy was found at just the right position. This object had two central cores close together, and it seemed likely that here was an example of two galaxies in direct head-on collision.

Apparently colliding galaxies are very efficient broadcasting stations, since in the radio wave-lengths these two galaxies are radiating a quarter of a million times as much energy as they would if not in collision. The stars in galaxies are so far apart relative to their own diameters that there is small chance of any stars colliding, even if two galaxies pass directly through each other. But the gas and dust of the two systems will meet at high velocity, and the energy of this impact seems to produce very strong radio waves. The correctness of this interpretation was checked by analyzing the light from the colliding galaxies of Cygnus A with the spectroscope. The spectrum was found to contain bright lines of the type that could only be produced by a very hot, highly excited gas.

It should be noted here that a number of astronomers, including a group in the U.S.S.R., do not accept the collision hypothesis as an explanation of the intense radio emission from peculiar galaxies. An alternative view is that these are young galaxies of complex structure. The abnormally strong radio-

wave intensity is assumed to result from the explosions of large numbers of supernovae in these systems.

Collisions of galaxies are not an unexpected event. Suppose we return to our scale model of a large cluster of galaxies. We had 500 objects ranging from a foot in diameter down to the size of thumb tacks, all in a fifty-foot hall. Each galaxy has its own individual motion, and under these conditions an occasional traffic accident is bound to happen. We see many galaxies in apparent contact, or linked by long nebulous streamers like extensions of spiral arms. These streamers probably originate from tidal action at the time of near misses.

And now we return to the problem I mentioned earlier—why do the elliptical galaxies have no dust or gas? Perhaps the collisions are responsible as, after a few collisions, most of this material would be swept up or dispersed out of the systems. It is very significant that the gas-free elliptical galaxies are most common near the congested centres of large clusters, where collisions would be most frequent. On this view the spiral galaxies are those which have never had a collision, or at least have had very few collisions.

The peculiar galaxies of Cygnus A turn out to be over 700 million light-years away. The most distant object of this type yet identified may have the tremendous distance of 6,000 million light-years, and this seems near the limit of the present optical instruments. It is estimated that roughly a billion galaxies can be photographed with the 200-inch telescope. But of all the radio sources only a small fraction have been identified. Some can be explained by various types of sources in our own system, but a growing body of evidence indicates that most of the unidentified radio stars are very faint galaxies, possibly in full or grazing collisions, and these may never appear in optical telescopes. At the present time there is no good way of determining their distances by radio observations, but many are likely to be further away than the limits to which we can see with the 200-inch telescope. Already radio astronomy, the youngest branch of astronomical research, seems to have outstripped the other branches in surveying the universe.

OVER THE EDGE OF THE UNIVERSE

8

ONE of the oldest questions man has asked, and one of the most difficult to answer, is 'what kind of a universe do we live in?' Near the beginning of this book I referred to the rather naïve theories of the universe proposed by early man. Now we take a look at what the scientist of today has to say on the subject. I wonder if, to those living thousands of years in the future, our current thinking will also seem naïve and no more profound than the picture-writing of the cave men.

Cosmology is defined as the study or investigation of the universe as an orderly system. It deals essentially with the physical universe as a whole, rather than with any particular part or aspect. For example, the cosmologist attempts to find out whether the universe is bounded or unbounded, finite or infinite; whether it is the same now as it was in the past and will be in the future, or evolving so that the past was very different from the present, and the future will be something else again. Then there is the problem of our position in the universe. Are we in some special preferred position or are we in an average position? Does the universe as a whole appear the same from other locations as it does from the solar system?

From what I have said earlier you will realize that we have already learned a great deal about various types of objects in space, some of them very far removed from our solar system. It is natural that we know much more about the closer objects than we do concerning the very distant celestial bodies, since at the limits of observation our knowledge becomes uncertain

and our errors of measurement large. But it is on these very measurements, made of objects in the depths of space, that the cosmologist depends for his most valuable information.

The units which we can observe at these great distances are the galaxies, elliptical and spiral star systems far beyond our own Milky Way. To learn about the universe as a whole we must observe as much of it as possible. One of the major difficulties in cosmology is the fact that we, the observers, are restricted to one position in space. We must gather all our information from this one position, and this restriction will still be essentially the same even when travel within the solar system becomes commonplace.

To illustrate this point one can imagine a very intelligent race of ants isolated on a small island a few yards across. The ants have no way of crossing the water so they can't get off the island, but being very intelligent they decide to try to discover the kind of world they live in. So they make all kinds of measurements and observations from their few square yards of island in an attempt to decide whether the surface of the earth is curved or not, and whether the world is finite or infinite, and if finite how big it is. It is clear that the ants have set themselves a task which may seem impossible. And yet relatively, this is no more of a problem for the ants than is the theory of cosmology for man.

Is it then a hopeless case for us to attempt to learn the nature of the universe? Not entirely, but it is well to remember that the solutions so far advanced are tentative only and cannot be considered as close to a comprehensive or complete answer. Since the close of World War II rapid advances have been made as a result of the use of the 200-inch telescope on Mt. Palomar and of the introduction of powerful radio telescopes in both the northern and southern hemispheres. There hasn't been time as yet to assess fully the recent observational results, and in a few years the picture may have changed completely. But I will attempt to summarize the present state of knowledge, as this may help towards an understanding of the observational results and the cosmological theories which may be announced in the not too distant future.

To start with we can list certain items of information which have a bearing on the subject. Many of the heaviest elements are naturally radio-active, that is they produce small amounts of energy at a fixed rate, and during this process they change through a series of different elements, ending up eventually as some form of lead. When these radio-active elements occur in rocks from the earth's surface, or in the meteorites that arrive from other parts of the solar system, they leave evidence in this solid material of the radio-active transformation of heavy elements. Since each type of radio-activity proceeds at a certain rate which cannot be altered by the physical conditions, it is possible to estimate the ages of the rocks and meteorites by a careful analysis of their composition. Such methods of study give us a considerable range of ages for both rocks and meteorites, but we find an upper limit of age that is just under five billion years in both cases, so any system of cosmology must allow for the fact that the planets of the solar system have had solid surfaces for this long period of time.

Additional information on the time scale comes from a consideration of the stars, and the nuclear transformations which produce the energy to keep them shining. Knowing the mass of the stars, and the types of atomic cycles taking place in their interiors, it is possible to make an approximate estimate as to the length of time the atomic fuel within a star will last. The most recent studies by the English astronomer Fred Hoyle, and by others, indicate that the oldest stars in our galaxy may be nearly fifteen billion years old, that is three times the age of the oldest rocks on earth.

Important evidence concerning the nature of our universe is given by a study of the motions of the celestial bodies. This leads us directly to Newton's law of universal gravitation, a law which has been successfully applied to the prediction of the motion of masses wherever they exist in space. However, in the twentieth century, 250 years after Newton, Albert Einstein discussed the subject of motion and argued that there was no such thing as absolute motion. In other words objects do not move relative to an absolute and stationary space. The motion of a body can only be measured relative to the position of some

other body, or group of bodies. Einstein also postulated that the fastest relative motion that can be measured is the velocity of light, 186,000 miles a second. The theory of relativity was developed, starting from these two simple postulates.

It turns out that the classical equations of motion have to be changed. The numerical difference between the old and the new is very slight, except where relative motions approach the velocity of light, and here the change becomes appreciable. For example the nuclear physicist accelerates atomic particles to very high velocities in large machines such as cyclotrons. It has been found that the mass of these particles is greater when they are moving at these high velocities, and the increase in mass agrees exactly with that predicted by the equations of Einstein. Another immediate derivation from these equations is the concept that mass and energy are two forms of the same entity and can be transformed, the one into the other. A very small mass is equivalent to a large quantity of energy, or $e = mc^2$ where e is energy, m is mass, and c is the velocity of light. The correctness of this concept has been demonstrated in a most spectacular way every time an atomic explosion is set off.

Newton's law of gravitation is actually a more restricted form of the general treatment proposed by Einstein. There are very few cases where the two differ enough for astronomical observations to provide a check but where this has been possible, as in the case of the changes in the orbit of Mercury, or in the bending of light rays passing near the sun, the reasoning in the general theory of relativity has been confirmed.

When dealing with the universe as a whole we should not assume that the ordinary three-dimensional geometry of Euclid is correct out to very great distances. Possibly three-dimensional space is curved, but this is extremely difficult to visualize. Let us return to our hypothetical community of intelligent ants on their small island, but suppose now that they are flat and live entirely in two dimensions on a flat island. They have no ability to even conceive of a third dimension, and could no more think of one ant jumping over another than we can imagine one person passing directly through another. These flat ants develop a complete plane geometry applicable to the surface they live on where the three interior angles of a triangle equal

exactly two right angles, and where parallel straight lines never meet. This geometry seems to be absolutely correct as long as the ants are confined to their island. But eventually they find a way of travelling farther afield over long distances, and now they discover that their two-dimensional universe shows evidence of curvature. On a large scale the three interior angles of a triangle are found to be greater than two right angles, and two parallel lines do meet eventually. Of course we, who are looking on in three dimensions, see that they are moving over the surface of a sphere and that their two-dimensional universe is curved, and is boundless but finite. The area of the surface is limited by the radius of the sphere, called the radius of curvature. We can extend this type of analogy by noting that the flat ants could be living on a more complicated form of surface, one with reverse curves that might be called saddle-shaped. In this case it would be boundless and infinite. If we call the first case positive curvature the second case would be negative curvature. Applying this to ourselves we must bear in mind the possibility that our own three-dimensional universe may be curved in a somewhat analogous way.

Einstein demonstrated the difficulty of separating the concept of space from the concept of time. An event must take place in both space and time. We learn about the universe by observation, but the light waves and radio waves which carry the information all move at a finite velocity. An observer timing a clock on a moving object will find that it is running slow, relative to an identical clock at his own position, and the higher the relative velocity the slower the moving clock will seem to run. The old idea that time is the same for everyone everywhere in the universe must be discarded. In the general theory of relativity both space and time appear together in the equations, and time is treated like a fourth dimension.

When Einstein's equations for space-time are solved, it is found that there are a number of solutions and each solution gives a possible model of the universe. We have to decide from observation which is closest to the actual case. No simple solution gives a static model; but one set of solutions corresponds to an expanding universe, another to a universe which oscillates, first expanding, then contracting and so on. When we

speak of an expanding universe it doesn't mean just that objects within a fixed space are moving away from each other. We think rather of space itself expanding along with everything in it.

But now we must leave theory and take a look at the evidence of astronomical observations. We recognize the fact that we are on a small planet moving about the sun, and that the sun is some 26,000 light-years to one side of the centre of our star system or galaxy. It is even possible that our whole galaxy is some forty to fifty million light-years off to one side of a super-cluster of galaxies, centred in the direction of the constellation Virgo. But after noting these local irregularities we find that, in the large-scale picture, there are roughly the same numbers of galaxies, or clusters of galaxies, in all directions in space. In other words the general features of the universe appear much the same no matter which way we look. We can assume that other observers, no matter where they are located in the universe, will also have the same general view. This is called the cosmological principle, and according to this the assumption is made that we are not in any special or preferred position in the universe.

The most significant astronomical observation that has a bearing on cosmological theory results from an analysis of the light from distant galaxies by means of the spectroscope. The light from a galaxy consists of a compound blending of the light of all the stars and luminous gas in the galaxy. When this light is spread out into a spectrum it shows well-recognized features at certain wave-lengths, but it was found that on the average these features in the spectra of the galaxies were all shifted towards the red end of the spectrum. This striking observation was made originally by V. M. Slipher at the Lowell Observatory and extended later by E. P. Hubble and M. L. Humason at the Mt. Wilson Observatory. It was also found that the fainter the galaxies, the greater was the displacement to the red. The only logical physical explanation of this red shift, and the one now generally accepted by practically all astronomers, is that the distant galaxies are moving away from us, and that the red shift is due to what is called the Doppler effect. The light from a receding source is affected by the speed

of recession and appears to an observer to have a lower frequency, and thus a longer wave-length, than a similar source which is not receding. Since the fainter galaxies on the average are more distant than the brighter ones, and since these are the objects which exhibit the greater red shift, it appears that this effect is one which increases with distance. When we work out the velocities of recession that correspond to the observed red shifts we find that these are very large, extending up to velocities that are an appreciable fraction of the velocity of light.

If we wish to find the nature of any general law that governs this observed recession of the galaxies, we must combine the results of velocity measures made on many different galaxies, so that small individual peculiarities are averaged out. The distant galaxies show a definite tendency to group themselves into clusters, and it is usual to take average values for each cluster of galaxies. The two observational quantities that can be measured directly are the brightness of a galaxy and its speed of recession. In each cluster of galaxies we find a large range of brightness, from the giant galaxies down to the little dwarf galaxies, but, as noted before, there is a fairly standard upper limit of absolute brightness. Hence, for each cluster of galaxies we can establish the apparent brightness of the most luminous member of the cluster. This apparent brightness varies greatly from cluster to cluster, and we can consider this variation as primarily a distance effect. The faintest galaxies whose velocities have been measured are close to one million times fainter than the faintest stars visible to the naked eye, and on the stellar magnitude scale this is near the twenty-first magnitude.

If now we examine the velocities of recession in relation to the relative distances found from the brightness of the galaxies, we find that a simple law relates velocity to distance. The galaxies in a cluster in Ursa Major appear about one-ninth as bright as similar galaxies in Perseus. We conclude that the Ursa Major galaxies are three times as far away as those in Perseus, and we find they have three times the velocity of recession. Thus the velocity of recession increases in direct proportion to the distance and this proportionality seems to hold to the present limit of observation *(Fig. 26)*.

So all distant galaxies in the universe are receding from our galaxy, and the fainter and further away these galaxies are, the faster they are moving. At this point someone is almost sure to say that this observation disproves the cosmological principle, and shows that we *are* in a special location in the universe. However, a moment of reflection will make it clear that, if the speed of recession is strictly proportional to distance, then it means that the entire universe is expanding or growing bigger at a uniform rate, and observations made from any point in the universe will give exactly the same results as those we have found. Eddington used to use the illustration of a toy balloon. Suppose each cluster of galaxies is represented by a spot on this balloon. As you blow it up, each spot will separate from every other spot on the balloon, and the speed of separation will be proportional to the distance between each pair of spots.

The measurement of the velocities of the very faint galaxies is a difficult problem. It requires the use of the world's most powerful telescopes, and in some cases photographic exposures of over fifty hours' duration have been necessary. In recent years the large radio telescopes have been of great assistance here. Certain peculiar galaxies send out very strong radio waves, and can be identified fairly easily with radio telescopes even though they are very inconspicuous in optical instruments. By a fortunate chance the gas in these peculiar galaxies shines brightly, and produces a spectrum which makes it easy to measure a velocity. Hence, once the position of a peculiar galaxy is determined with a radio telescope, the velocity can be measured by photography with the 200-inch telescope on Mt. Palomar. This technique is a very good example of the type of co-operation that is often necessary in astronomy. It has made possible the measurement of some velocities in a very distant cluster of galaxies in the constellation Boötes, giving a value of recession 86,000 miles per second, nearly half the velocity of light.

With more powerful telescopes, or new techniques, we may be able to observe objects well beyond these galaxies in Boötes, and for these the velocity of recession may be close to that of light. The limit of the universe available to observation will be reached when the velocity of recession equals that of

light. No light or radio waves can reach us from beyond this distance. As a matter of fact this explains why we have a dark sky, and provides the solution to a famous paradox of the nineteenth century. A hundred years before the expansion of the universe was discovered it was shown by Olbers that if the universe was evenly populated with stars to infinity the sky should appear infinitely bright, no matter how thinly the stars were spaced. But Olbers tacitly assumed a static universe not an expanding one, and didn't realize the true explanation of his paradox.

In this discussion of the expansion of the universe I have said nothing about the actual distances of the clusters of galaxies.

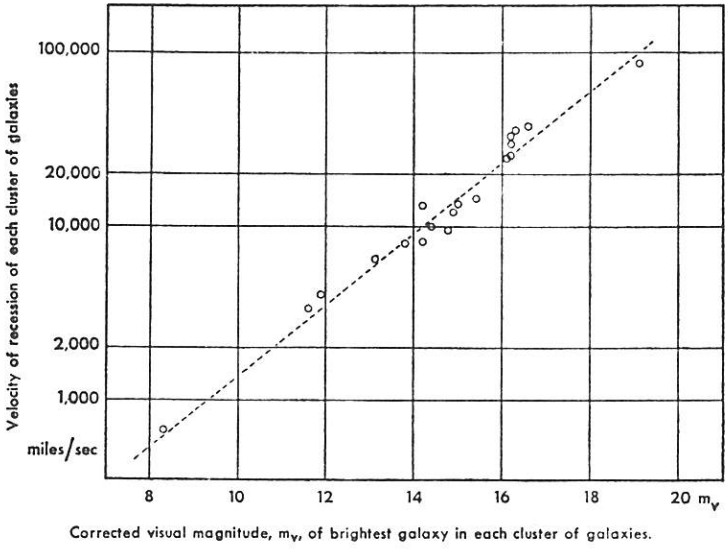


FIG. 26. A plot of the velocities of the galaxies against a standardized apparent magnitude for the brightest member of each cluster, using data published by M. L. Humason, N. U. Mayall, A. R. Sandage, and R. Minkowski.

This omission has been deliberate. The brightnesses and velocities of the galaxies are observational quantities about which there is no great uncertainty. But though we know relative distances we do not have a reliable value for the absolute distances. It is like having a good road map without a scale of miles to go with it. Over the last ten years the distance scale to be used for clusters of galaxies has gradually increased, until now it is somewhere between five and ten times larger than it was in 1950. For this reason you will find large discrepancies in the distances quoted in various articles and books published during recent years. Since discussion of this subject is still very active I can't yet give you a good value for the distance scale. The most recent estimates suggest that a recession of 100 miles per second corresponds to a distance of five million to seven million light-years, with current thinking tending towards the larger value. On this basis the distance of the faintest galaxies whose velocities have been measured is 6,000 million light-years, but this should be considered as a tentative value at the present time.

Now we return to a consideration of possible models of the universe. Whatever the distance scale, the observation of the expansion of the universe seems to fit well into one set of solutions of the equations based on the general theory of relativity. The type of expansion we find suggests that at some time in the distant past all the galaxies were very much closer together, and may have formed an extremely compact, condensed universe. The length of time since this condition existed will depend on the distance scale, and on whether we assume that the speed of expansion has remained constant or not. A constant expansion would indicate a continually decreasing density of matter in the universe, a one-way trend from which there is no return. A slowing down of the expansion would indicate an oscillating universe, where the expansion might eventually stop, reverse itself and become a contraction. On the basis of either of these models the contemporary universe is different from what it was in the past. The most recent values of the distance scale give us periods between eight and fourteen billion years since the galaxies were in a concentrated group.

This time scale fits much better with the known ages of the planets and the estimated ages of the stars, than does the value based on the old distance scale.

The models of the universe we have just been discussing may be classed as evolving, or evolutionary, models. A completely different type of model was first proposed at Cambridge University in 1948 by Herman Bondi and Thomas Gold, and in a slightly different form by Fred Hoyle. A significant contribution was also made by W. H. McCrea of Royal Holloway College, Surrey. This new model is called the steady-state theory of the universe, and makes the assumption that the large-scale features of the universe not only appear the same from every point of observation, but that they have not varied with time. To compensate for the decreasing density that results from the recession of the galaxies, it is assumed that enough hydrogen atoms are continually formed in space, or created if you like, to maintain a constant over-all density. This new matter would gradually condense into galaxies and stars, which would then continually replace those moving out of sight as a result of the steady expansion. On the basis of this theory we might have much more matter existing as invisible gas between the galaxies than appears as visible matter in the galaxies. The required rate of creation of hydrogen is very small: one new atom in a space the size of an ordinary room every few million years. This rate is far below anything that could be detected by physical measurements.

Is a test of the steady-state theory then quite out of the question? Not at all! As its originators have pointed out, the steady-state model is more susceptible to observational tests than any of the other models. In a steady state universe the average density of galaxies in space at the present time is the same as it was thousands of millions of years ago, while in the expanding evolutionary model the number of galaxies in a given volume of space is smaller now than it was in the past. In a steady-state universe, since new galaxies are forming everywhere at a standard rate, all parts of space should show the same distribution of young, middle-aged, and old galaxies, and this will not change with time. In an evolutionary model we would expect an over-all average aging of the galaxies with time.

Now it may be possible to test for some of these aging effects. As we look out to greater and greater distances in space we go further and further back into time. It takes light eight minutes to reach us from the sun, so we see the sun as it was eight minutes ago. The closest star, apart from the sun, is four light-years away, and we see it as it was four years ago. The Andromeda nebula is seen as it was two million years ago, and light from the distant clusters of galaxies is thousands of millions of years old. Hence, we see these objects so far back into the past, it might be possible to use them to help us decide which model of the universe agrees most closely with observation. For example, if the very distant galaxies seem distributed in much the same way as those nearby, this would be support for the steady-state model; but if the distant galaxies are more crowded together than the closer ones, this would support the evolutionary universe.

Counts of galaxies made with optical telescopes do not yet give any clear indication of a marked increase in the density of galaxies as we go back in time. However, thanks to the radio waves sent out by peculiar galaxies, it is believed that radio telescopes can reach further out into space, and thus further back into time, than the largest optical instruments. The latest survey of these distant radio sources by Martin Ryle at the Mullard Radio Astronomy Observatory, Cambridge, England, seems to give a fairly definite indication that peculiar galaxies, and therefore galaxies as a whole, are more crowded together at the limits of observation in the depths of space. This is strong observational support for an evolutionary model of the universe.

The way in which the recession of the galaxies varies with their brightness should help us to choose between an oscillating evolutionary model, and one which is not oscillating. If the expansion has slowed down with time there should be evidence of a faster rate of expansion in the faintest galaxies. So far there seems to be no significant trend in this direction, but a positive decision is difficult because we don't know how the brightness of a galaxy changes with time. To summarize, we may say that at present observations seem to give some support to a uniformly expanding, infinite, evolutionary universe. But

the steady-state universe has many attractive and plausible features, and the discussion is still very much open.

It may seem strange that though stars, galaxies, and clusters of galaxies, are held together by gravitational forces, the clusters themselves are moving away from each other. What is it that overcomes the force of gravity at great distances? R. A. Lyttleton has made an interesting suggestion to explain this. Electrical forces between positive and negative charges are very many times greater than the gravitational forces, and we may have electrical forces of either attraction or repulsion. It has always been assumed that in normal matter the positive charge on the proton exactly balances the negative charge on the electron. But suppose the positive charge is very slightly in excess of the negative, by one part in a million million million. This is far too small to detect experimentally, but, since like charges repel, it would be enough to cause the observed expansion of the universe. The presence of a few extra electrons, or negative charges, in concentrations of matter such as galaxies, would preserve the control of gravity within these units. So far it has not been possible to test this theory by experiment.

In conclusion, I feel that I should comment on a suggestion made by some, that the initial, very dense state of matter in the evolutionary model can be associated with God's creation of the universe, and that somehow this model is more acceptable on religious grounds than the steady-state model. I do not believe that religion enters the problem here at all. Our cosmological theories are simply attempts to use the methods of physical science for describing large-scale order in the universe. The understanding of God is far beyond the limited techniques of the scientific method. His creative act should not be identified with a mathematical singularity, and God cannot be confined to, or described within, a dimensional framework of space and time.

APPENDIX A

PHYSICAL DATA FOR PLANETS AND SATELLITES

NAME	SYMBOL	MEAN RADIUS OF ORBIT (MILLIONS OF MILES)	PERIOD OF REVOLUTION (DAYS OR YEARS)	MEAN VELOCITY IN ORBIT (MILES/SEC)	EQUATORIAL DIAMETER (MILES)	POLAR DIAMETER (MILES)	MEAN DENSITY (WATER = 1)	ESCAPE VELOCITY AT SURFACE (MILES/SEC)	APPROXIMATE MEAN SURFACE TEMPERATURE (°F)	REFLECTING EFFICIENCY OR ALBEDO	BRIGHTEST STELLAR MAGNITUDE	NUMBER OF NATURAL SATELLITES
MERCURY	☿	35.98	88.0d	29.7	3010	3010	5.5	2.7	*+660° †−410°	0.06	−1.9	0
VENUS	♀	67.24	224.7d	21.8	7610	7610	5.0	6.5	>+500°	0.7	−4.4	0
EARTH	⊕	92.96	365.3d	18.5	7927	7900	5.52	7.0	+60°	0.4		1
MARS	♂	141.6	687.0d	15.0	4150	4130	4.1	3.2	*+70° †<−10°	0.15	−2.8	2
CERES	①	257.2	4.60y	11.1	480	480				0.06	+7.4	0
JUPITER	♃	483.6	11.86y	8.1	89900	83900	1.3	38.	−210°	0.5	−2.5	12
SATURN	♄	886.7	29.46y	6.0	75500	67500	0.7	23.	−250°	0.5	−0.4	9
URANUS	♅	1783.	84.01y	4.2	30600	28600	1.6	14.	<−300°	0.7	+5.7	5
NEPTUNE	♆	2794.	164.8y	3.4	27100	26500	2.5	16.	<−300°	0.6	+7.6	2
PLUTO	♇	3673.	248.4y	3.0	4000?	4000?	4?	3?	<−300°	0.15?	+15.	0
MOON	☾	0.2389	27.32d	0.64	2162	2160	3.3	1.5	*+250° †−240°	0.07	−12.6	
TITAN		0.759	15.95d	3.5	3000	3000	2.4	1.7	−240°	0.3	+8.2	

*Centre of bright hemisphere

†Centre of dark hemisphere

See also Figure 8, page 19.

APPENDIX B

ASTRONOMICAL UNITS AND CONSTANTS

1 *inch* = 2.540000 centimetres (cm)
1 *mile* = 1.609344 kilometres (km)
1 *pound* = 0.4536 kilograms (kg)

1 inch = 2½ cm	1 cm = ⅖ inch
1 mile = 1⅝ km	1 km = ⅝ mile
1 pound = 5/11 kg	1 kg = 2⅕ pounds

1 *micron* (μ) = $\frac{1}{10{,}000}$ cm (10^{-4} cm)

1 *angstrom unit* (A) = $\frac{1}{100{,}000{,}000}$ cm (10^{-8} cm)

1 *astronomical unit* (au) = mean distance earth to sun = 92,956,000 miles (9.3×10^7 miles)

velocity of light = 186,282 miles/sec = 299,792 km/sec (3×10^{10} cm/sec)

1 *light-year* (ly) = distance light travels in year = 5,880,000,000,000 miles (6×10^{12} miles)

1 *parsec* (ps) = 3.26 light-years = 19,170,000,000,000 miles (2×10^{13} miles)

1 *kilocycle* (kc) = 1,000 per second

1 *megacycle* (Mc) = 1,000,000 per second

temperature scales

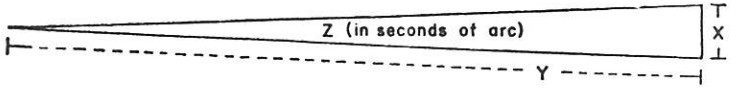
Fahrenheit	Centigrade	Kelvin
−460°F	−273°C	000°K
+032	000	+273
+212	+100	+373
+572	+300	+573
+932	+500	+773

angular measure

1 degree (°) = 60 minutes of arc (′)
1 minute of arc = 60 seconds of arc (″)

star magnitudes	*relative brightness*
16th	1/10,000
11th	1/100
6th	1
5th	2½
4th	6¼
3rd	16
2nd	40
1st	100
−4th	10,000

absolute magnitude = the magnitude a star would have if viewed from a distance of 10 parsecs



In observational astronomy it is frequently necessary to measure very small angles. In the above triangle if lengths x and y are expressed in the same unit, and z in seconds of arc, then

$$\frac{x}{y} = \frac{z''}{206{,}000}$$

and knowing any two of the unknown quantities you can calculate the third.

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